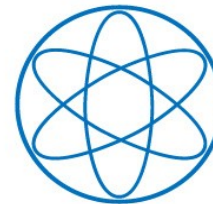


Production and signatures of multiflavour dark matter scenarios

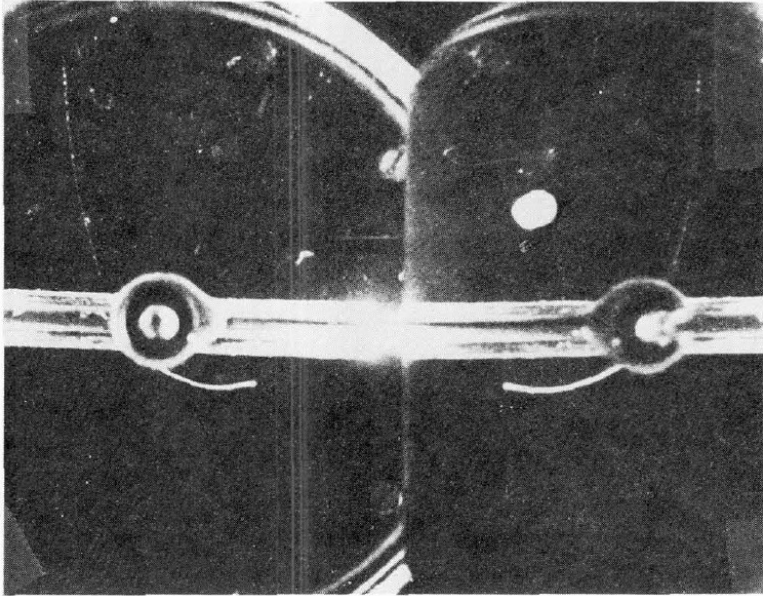
Alejandro Ibarra



Based on 2103.10392, 1912.09458, in collaboration with Johannes Herms.

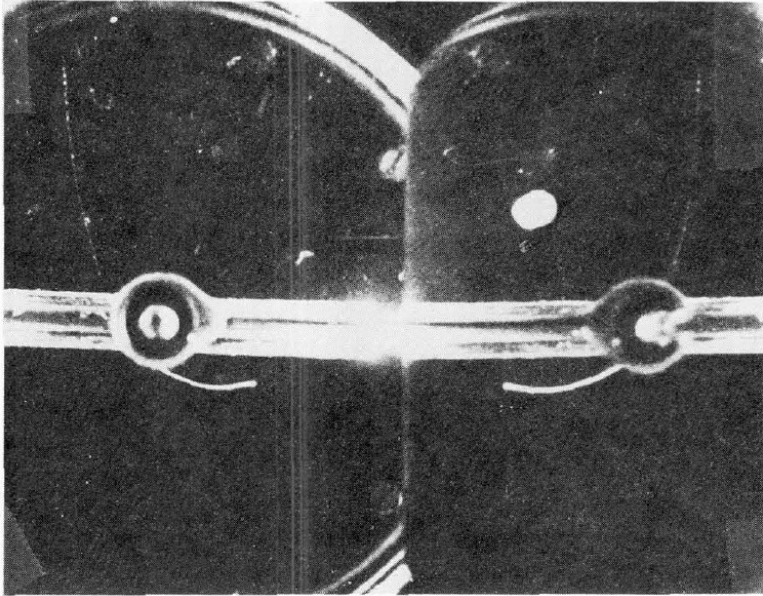
MOCa
June 8th, 2021

Introduction



Anderson, Neddermeyer '36

Introduction

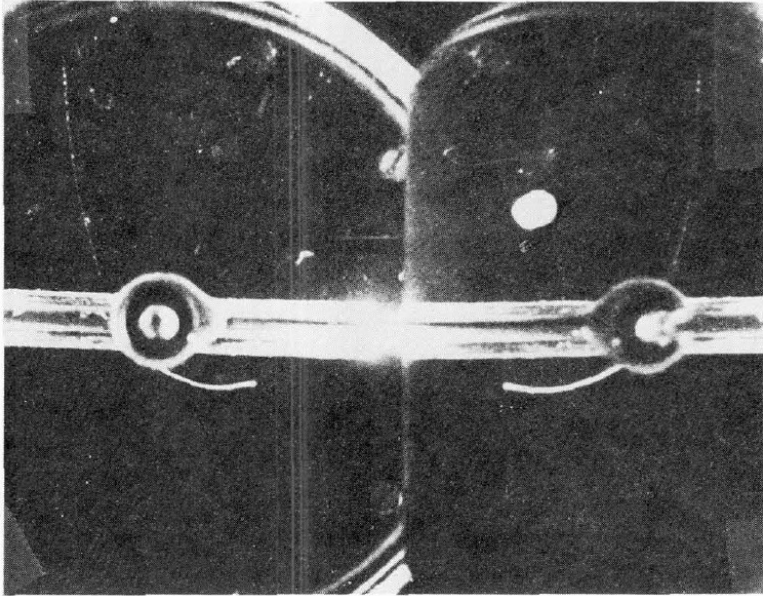


Anderson, Neddermeyer '36

Same charge as the electron.
Mass between the electron and the proton mass.

Meson

Introduction

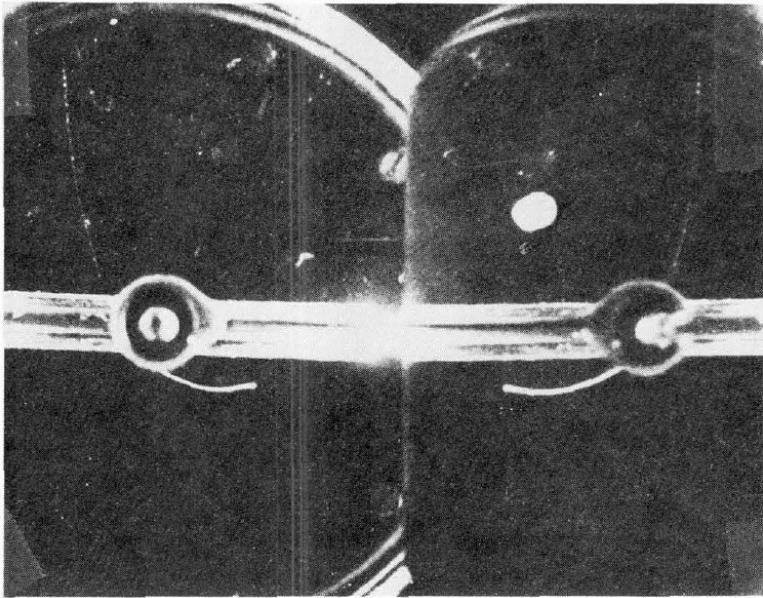


Anderson, Neddermeyer '36

Same charge as the electron.
Mass between the electron and the proton mass.

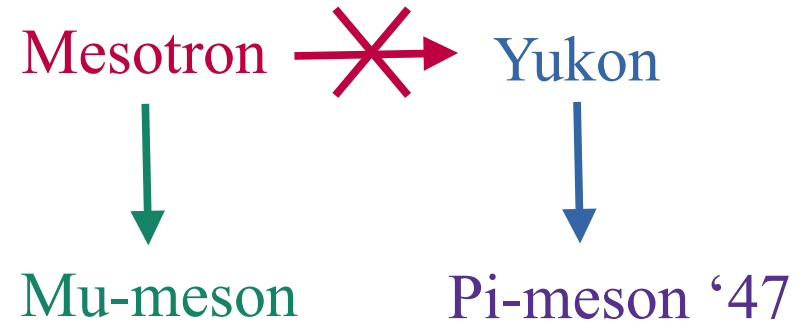
Meson \longrightarrow Yukon

Introduction

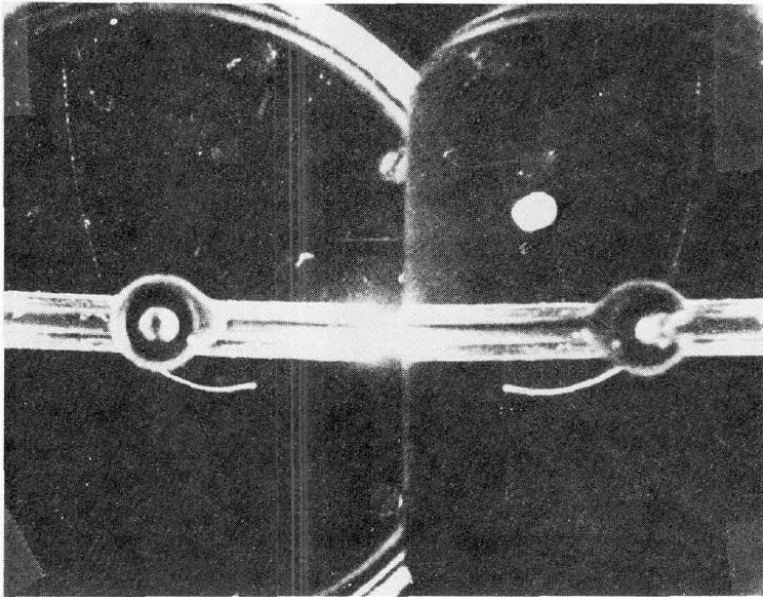


Anderson, Neddermeyer '36

Same charge as the electron.
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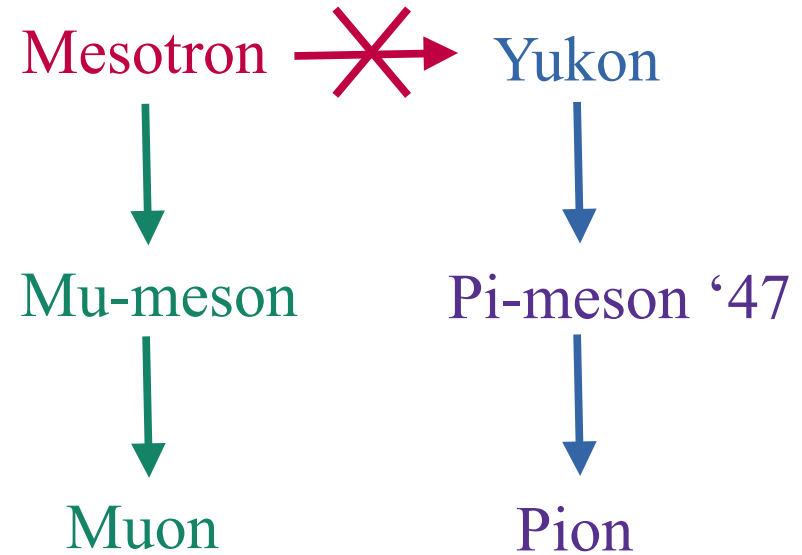


Introduction

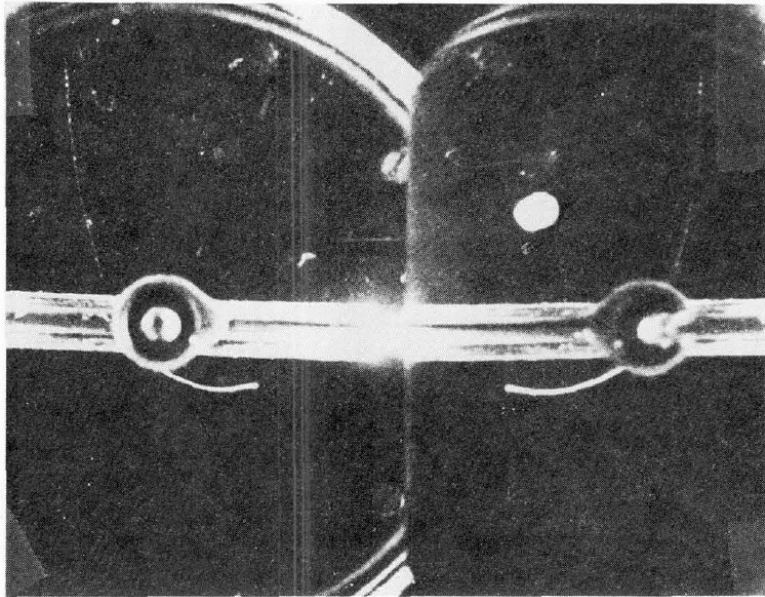


Anderson, Neddermeyer '36

Same charge as the electron.
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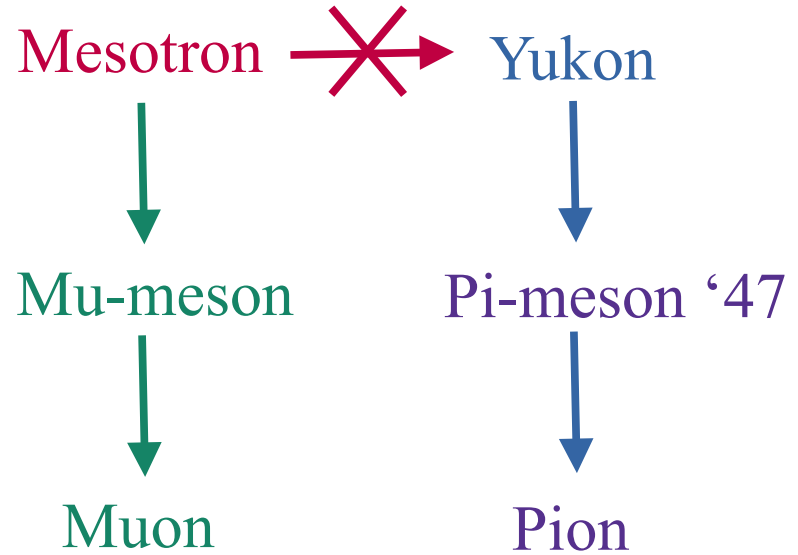


Introduction



Anderson, Neddermeyer '36

Same charge as the electron.
Mass between the electron and the proton mass.



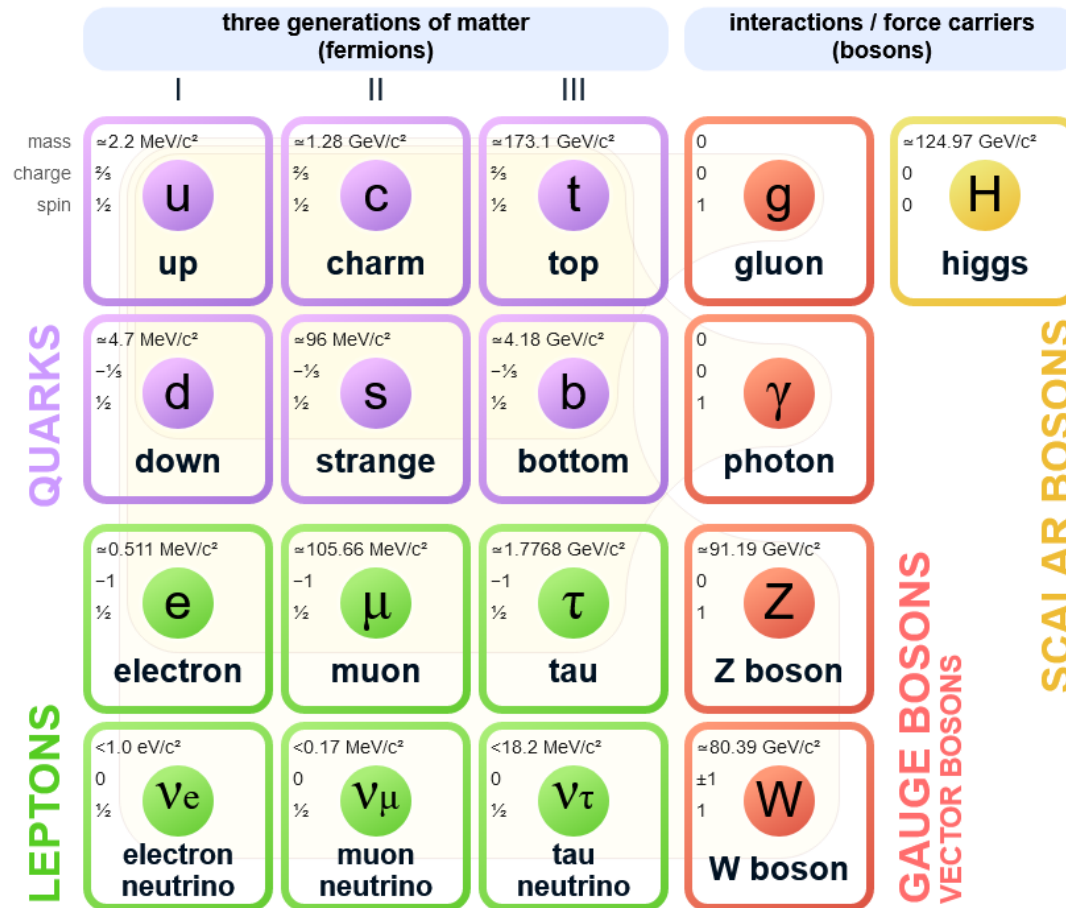
Who ordered that?!



Isidor Rabi

Introduction

Standard Model of Elementary Particles

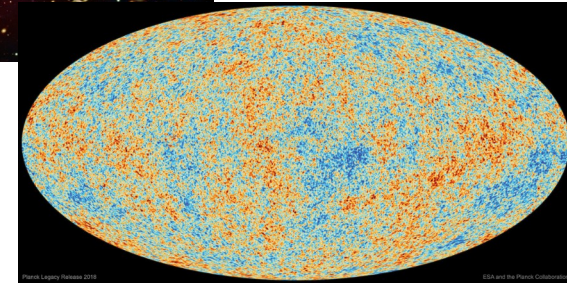
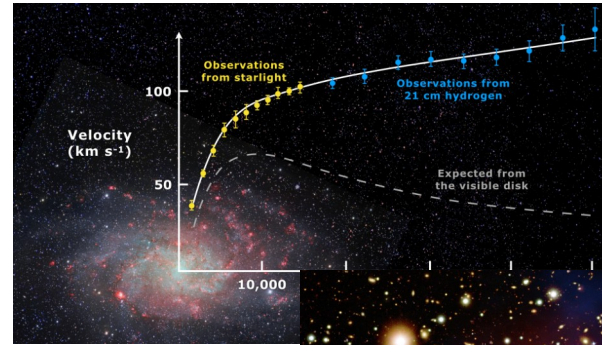
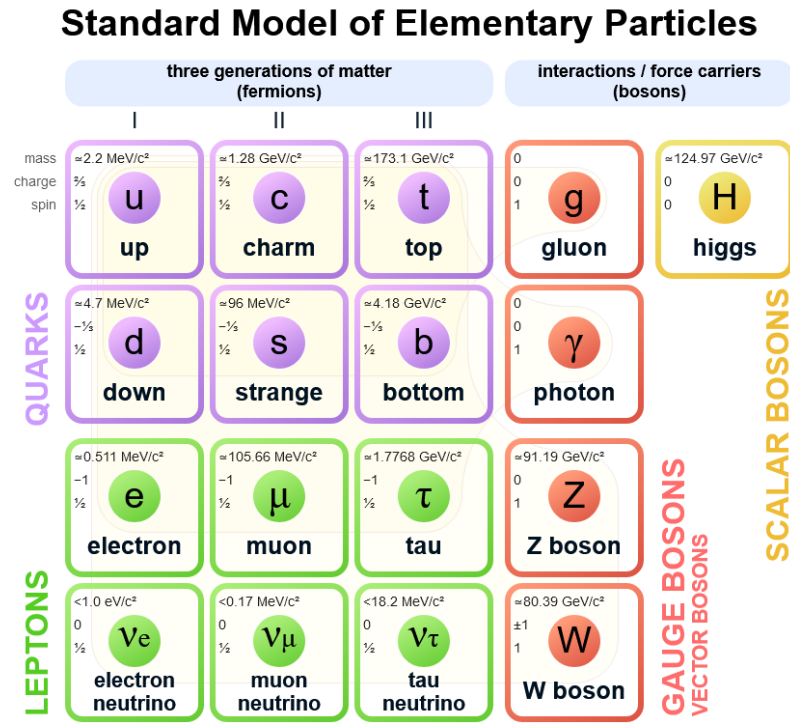


As of today, we still don't understand why all known fermions are replicated three times, with different masses (Yukawa couplings?)

Introduction

- **Who ordered the heavier generations?** Our Universe today is mostly made of first generation fermions: u,d,e (plus three massive neutrinos).
- However, the heavier generations could have played a crucial role in shaping our Universe (CP violation in baryogenesis)
- Also, the heavier generations lead to many phenomena in experiments, which helped to elucidate the structure of the Standard Model.

Introduction



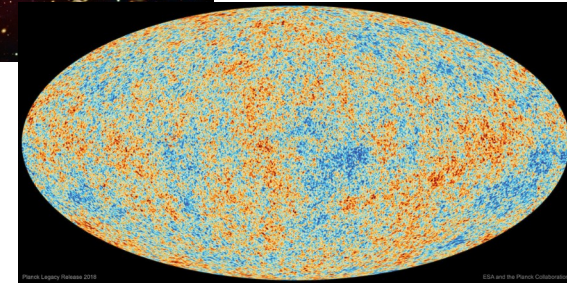
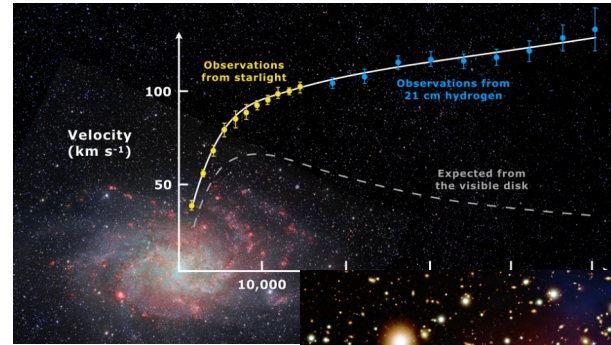
It is highly probable that the Standard Model has to be extended → a dark matter particle?

Introduction

Standard Model of Elementary Particles

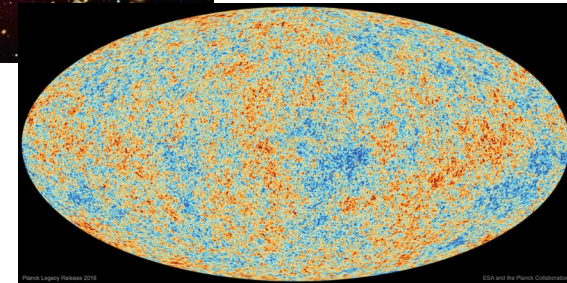
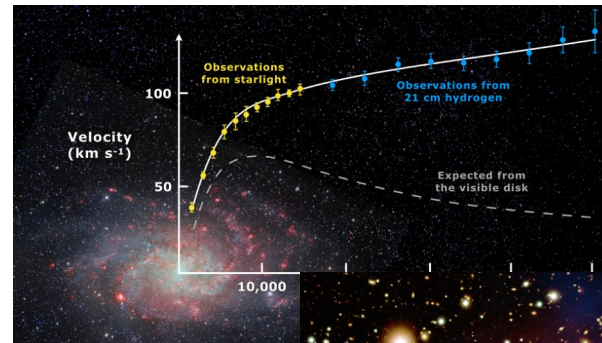
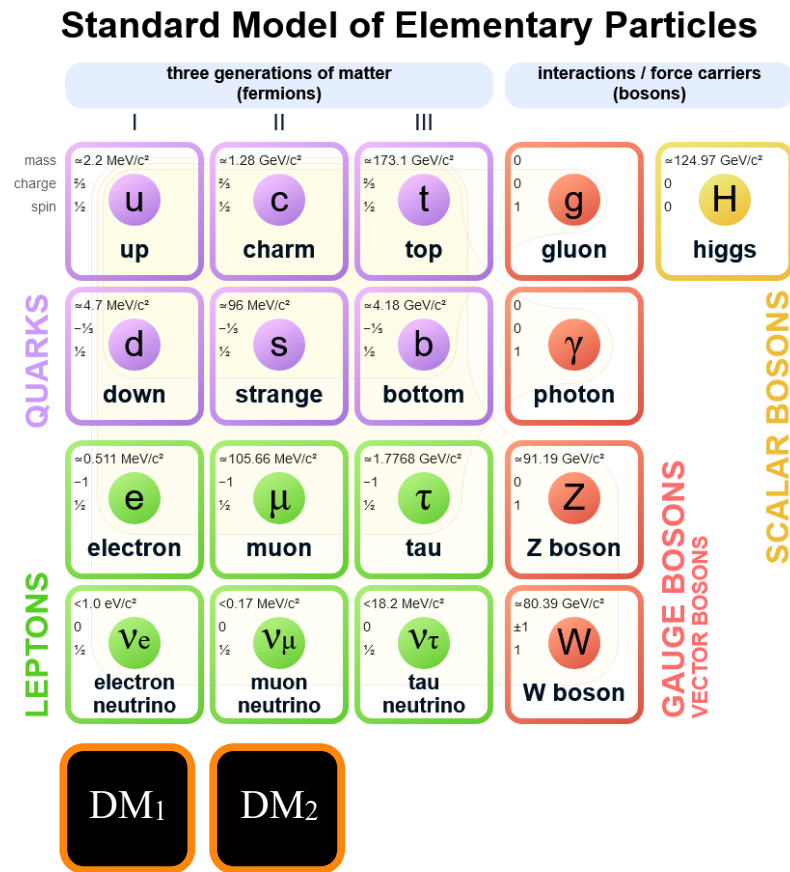
three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
QUARKS	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS					GAUGE BOSONS
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	VECTOR BOSONS
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

DM₁



It is highly probable that the Standard Model has to be extended → a dark matter particle?

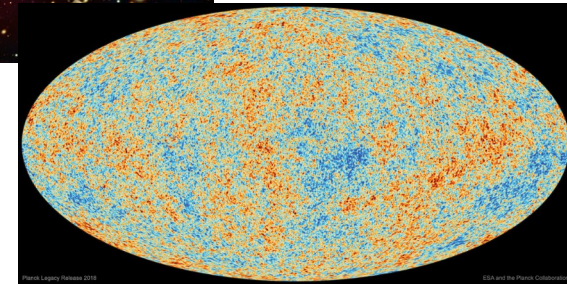
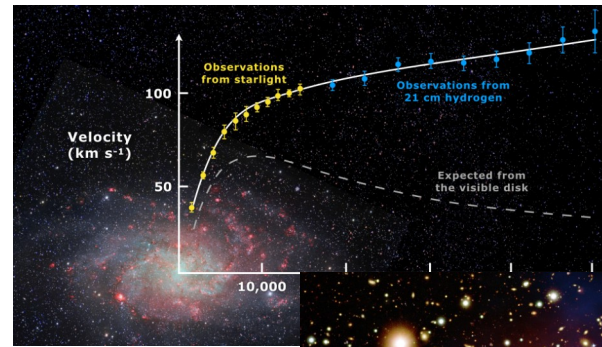
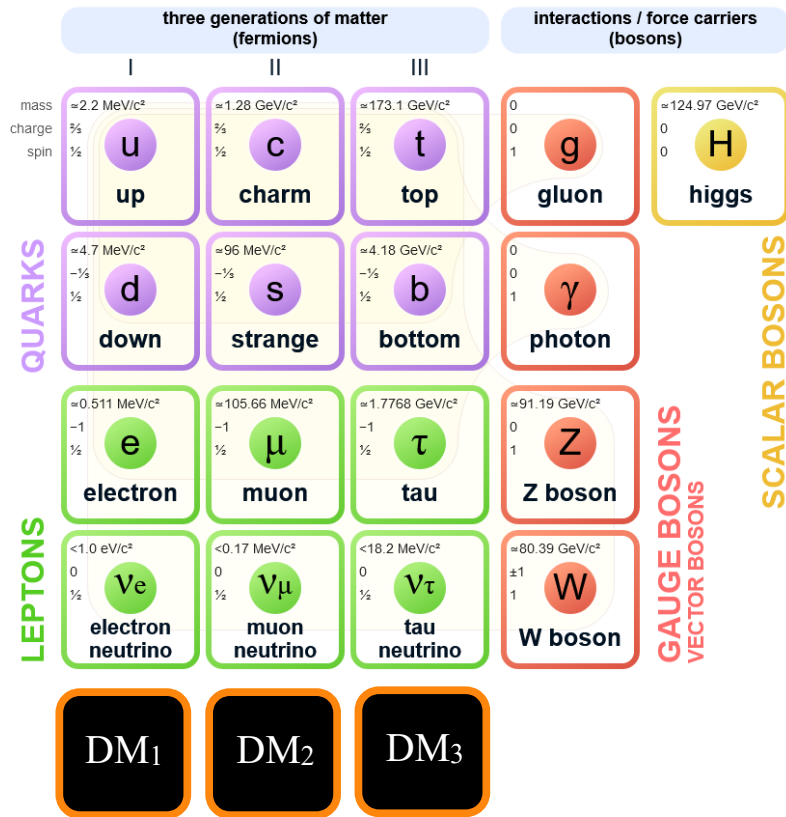
Introduction



It is highly probable that the Standard Model has to be extended → a dark matter particle?

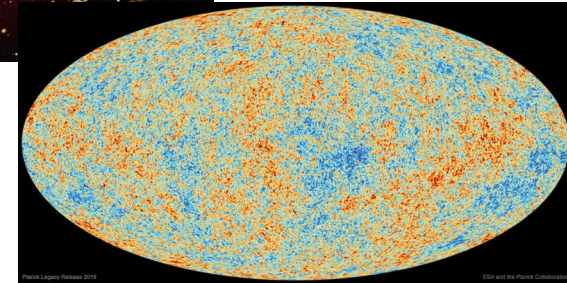
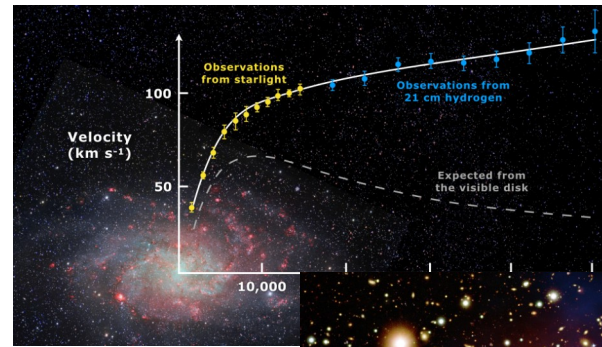
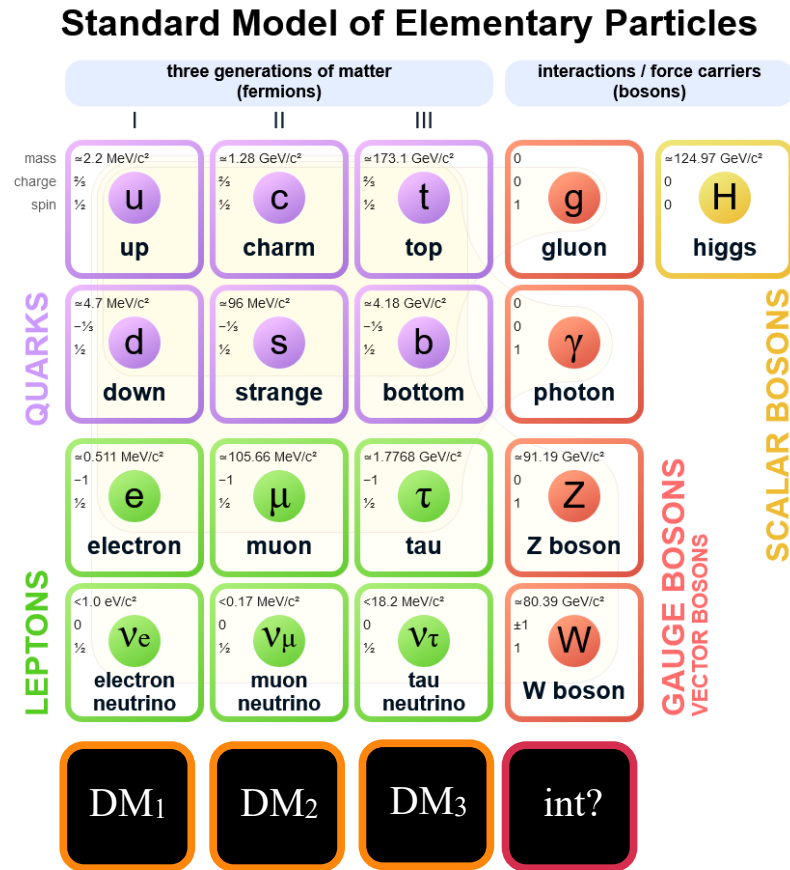
Introduction

Standard Model of Elementary Particles



It is highly probable that the Standard Model has to be extended → a dark matter particle?

Introduction



It is highly probable that the Standard Model has to be extended → a dark matter particle?

Introduction

- **Who ordered the heavier generations?** Our Universe today is mostly made of first generation fermions: u,d,e (plus three massive neutrinos).

Could the DM be made by two long-lived components?

- However, the heavier generations could have played a crucial role in shaping our Universe (CP violation in baryogenesis)

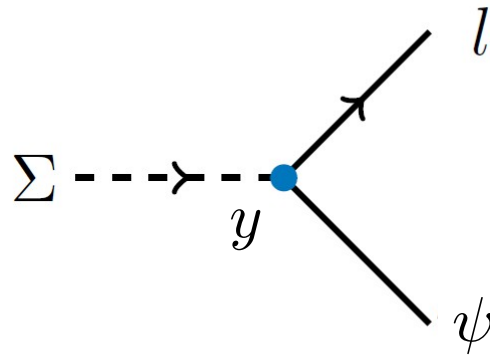
Could the heavy DM flavors also play a role in shaping our Universe?

- Also, the heavier generations lead to many phenomena in experiments, which helped to elucidate the structure of the Standard Model.

Could the heavy DM flavors lead to new signals, that will help us elucidate the structure of the dark sector?

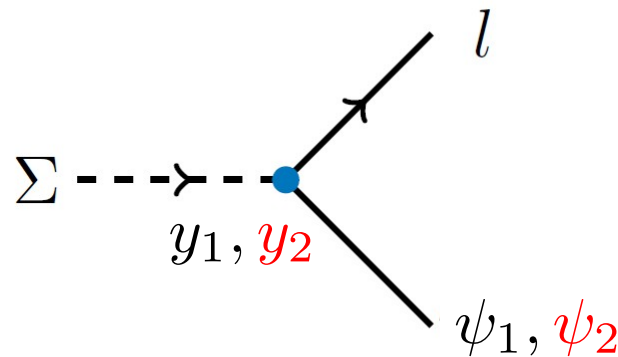
A toy model of multiflavor DM

- Consider a Majorana singlet fermion as DM candidate. Assume that it couples to the right-handed leptons through a scalar mediator Σ .



A toy model of multiflavor DM

- Consider a Majorana singlet fermion as DM candidate. Assume that it couples to the right-handed leptons through a scalar mediator Σ . **Add a second generation of the Majorana singlet fermion.**



- Free parameters: $m_1, m_2, m_\Sigma, y_1, y_2$ (+ quartic couplings)

Dark matter production

initial state		final state		y_i scaling
Σ^+	Σ^-	γ	γ	1
		γ	Z	
		Z	Z	
		W^+	W^-	
		H	H	
		H	Z	
		q	\bar{q}	
		l^+	l^-	$1, y_1^2, y_1^4, y_2^2, y_2^4, y_1^2 y_2^2$
Σ^+	Σ^+	l^+	l^+	$y_1^4, y_1^2 y_2^2, y_2^4$
ψ_i	Σ^+	l^+	γ, Z	y_i^2
ψ_i	ψ_j	l^+	l^-	$y_i^2 y_j^2$
ψ_i	l^\pm	ψ_j	l^\pm	$y_i^2 y_j^2$
Σ^\pm	γ, Z	ψ_i	l^\pm	y_i^2
Σ^\pm	l^\pm	ψ_i	γ	y_i^2
	Σ^\pm	ψ_i	l^\pm	y_i^2
	ψ_2	ψ_1	$l^+ l^-$	$y_1^2 y_2^2$

Dark matter production

initial state		final state		y_i scaling
Σ^+	Σ^-	γ	γ	1
		γ	Z	
		Z	Z	
		W^+	W^-	
		H	H	
		H	Z	
		q	\bar{q}	
		l^+	l^-	$1, y_1^2, y_1^4, y_2^2, y_2^4, y_1^2 y_2^2$
Σ^+	Σ^+	l^+	l^+	$y_1^4, y_1^2 y_2^2, y_2^4$
ψ_i	Σ^+	l^+	γ, Z	y_i^2
ψ_i	ψ_j	l^+	l^-	$y_i^2 y_j^2$
ψ_i	l^\pm	ψ_j	l^\pm	$y_i^2 y_j^2$
Σ^\pm	γ, Z	ψ_i	l^\pm	y_i^2
Σ^\pm	l^\pm	ψ_i	γ	y_i^2
	Σ^\pm	ψ_i	l^\pm	y_i^2
	ψ_2	ψ_1	$l^+ l^-$	$y_1^2 y_2^2$

Annihilation

Dark matter production

initial state		final state		y_i scaling
Σ^+	Σ^-	γ	γ	1
		γ	Z	
		Z	Z	
		W^+	W^-	
		H	H	
		H	Z	
		q	\bar{q}	
		l^+	l^-	$1, y_1^2, y_1^4, y_2^2, y_2^4, y_1^2 y_2^2$
Σ^+	Σ^+	l^+	l^+	$y_1^4, y_1^2 y_2^2, y_2^4$
ψ_i	Σ^+	l^+	γ, Z	y_i^2
ψ_i	ψ_j	l^+	l^-	$y_i^2 y_j^2$
ψ_i	l^\pm	ψ_j	l^\pm	$y_i^2 y_j^2$
Σ^\pm	γ, Z	ψ_i	l^\pm	y_i^2
Σ^\pm	l^\pm	ψ_i	γ	y_i^2
	Σ^\pm	ψ_i	l^\pm	y_i^2
	ψ_2	ψ_1	$l^+ l^-$	$y_1^2 y_2^2$

Co-annihilation

Dark matter production

initial state		final state		y_i scaling
Σ^+	Σ^-	γ	γ	1
		γ	Z	
		Z	Z	
		W^+	W^-	
		H	H	
		H	Z	
		q	\bar{q}	
		l^+	l^-	
Σ^+	Σ^+	l^+	l^+	$y_1^4, y_1^2 y_2^2, y_2^4$
ψ_i	Σ^+	l^+	γ, Z	y_i^2
ψ_i	ψ_j	l^+	l^-	$y_i^2 y_j^2$
ψ_i	l^\pm	ψ_j	l^\pm	$y_i^2 y_j^2$
Σ^\pm	γ, Z	ψ_i	l^\pm	y_i^2
Σ^\pm	l^\pm	ψ_i	γ	y_i^2
	Σ^\pm	ψ_i	l^\pm	y_i^2
	ψ_2	ψ_1	$l^+ l^-$	$y_1^2 y_2^2$

$\Sigma\Sigma$ pair annihilation

Dark matter production

initial state		final state		y_i scaling
Σ^+	Σ^-	γ	γ	1
		γ	Z	
		Z	Z	
		W^+	W^-	
		H	H	
		H	Z	
		q	\bar{q}	
		l^+	l^-	$1, y_1^2, y_1^4, y_2^2, y_2^4, y_1^2 y_2^2$
Σ^+	Σ^+	l^+	l^+	$y_1^4, y_1^2 y_2^2, y_2^4$
ψ_i	Σ^+	l^+	γ, Z	y_i^2
ψ_i	ψ_j	l^+	l^-	$y_i^2 y_j^2$
ψ_i	l^\pm	ψ_j	l^\pm	$y_i^2 y_j^2$
Σ^\pm	γ, Z	ψ_i	l^\pm	y_i^2
Σ^\pm	l^\pm	ψ_i	γ	y_i^2
	Σ^\pm	ψ_i	l^\pm	y_i^2
	ψ_2	ψ_1	$l^+ l^-$	$y_1^2 y_2^2$

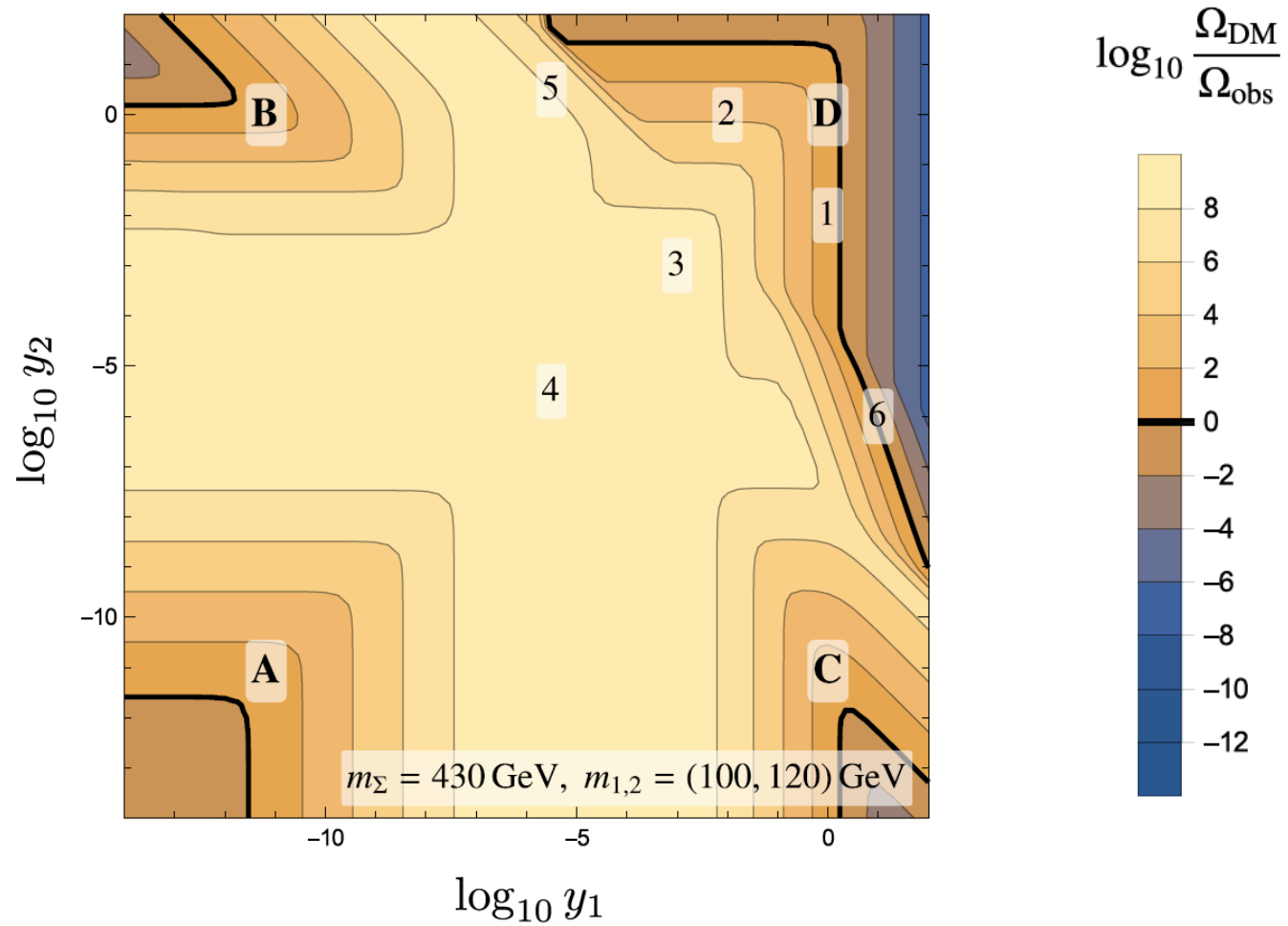
Conversion

Dark matter production

initial state		final state		y_i scaling
Σ^+	Σ^-	γ	γ	1
		γ	Z	
		Z	Z	
		W^+	W^-	
		H	H	
		H	Z	
		q	\bar{q}	
		l^+	l^-	$1, y_1^2, y_1^4, y_2^2, y_2^4, y_1^2 y_2^2$
Σ^+	Σ^+	l^+	l^+	$y_1^4, y_1^2 y_2^2, y_2^4$
ψ_i	Σ^+	l^+	γ, Z	y_i^2
ψ_i	ψ_j	l^+	l^-	$y_i^2 y_j^2$
ψ_i	l^\pm	ψ_j	l^\pm	$y_i^2 y_j^2$
Σ^\pm	γ, Z	ψ_i	l^\pm	y_i^2
Σ^\pm	l^\pm	ψ_i	γ	y_i^2
Σ^\pm		ψ_i	l^\pm	y_i^2
ψ_2		ψ_1	$l^+ l^-$	$y_1^2 y_2^2$

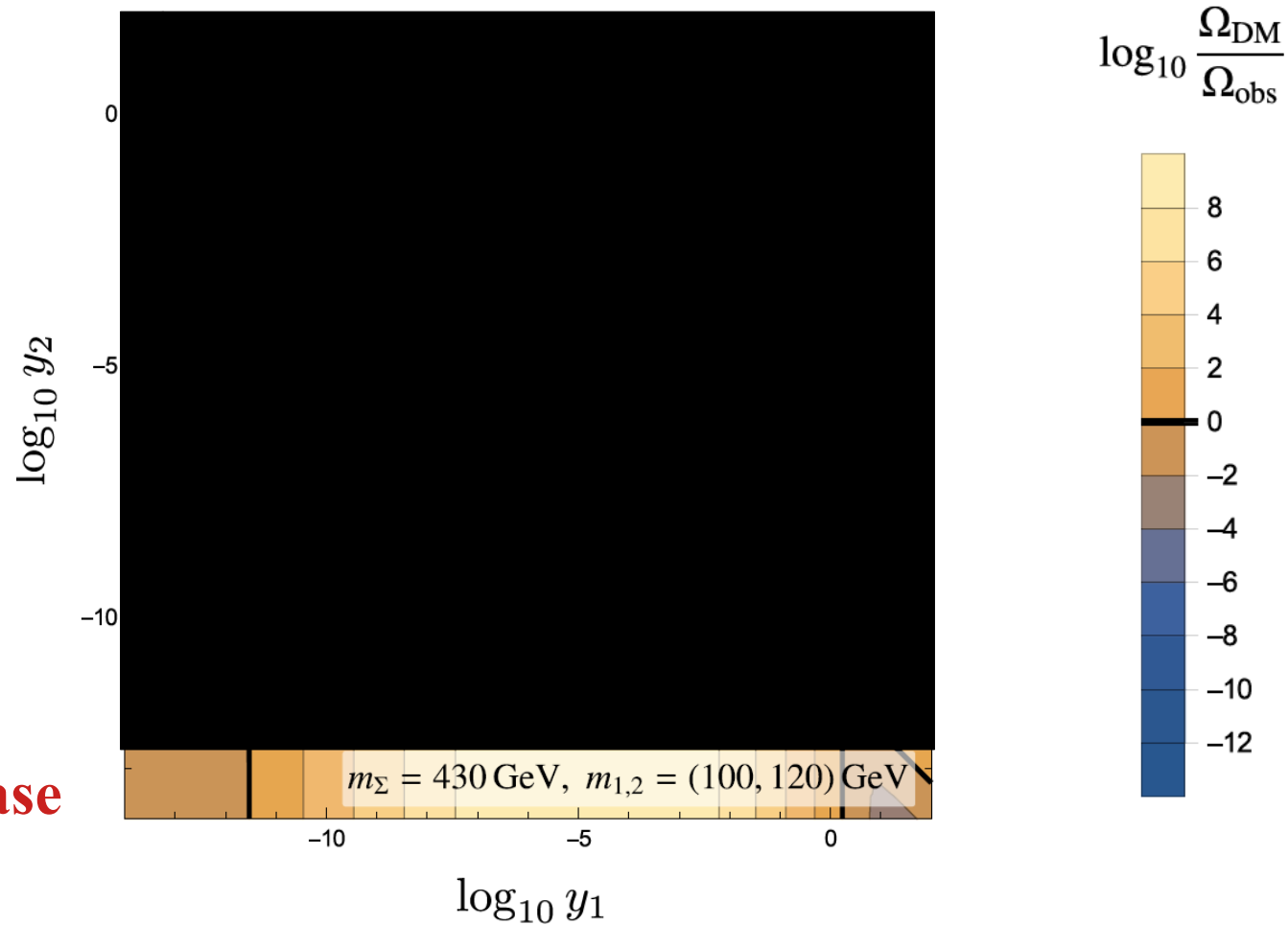
Decays (freeze-in)

A toy model of multiflavor DM

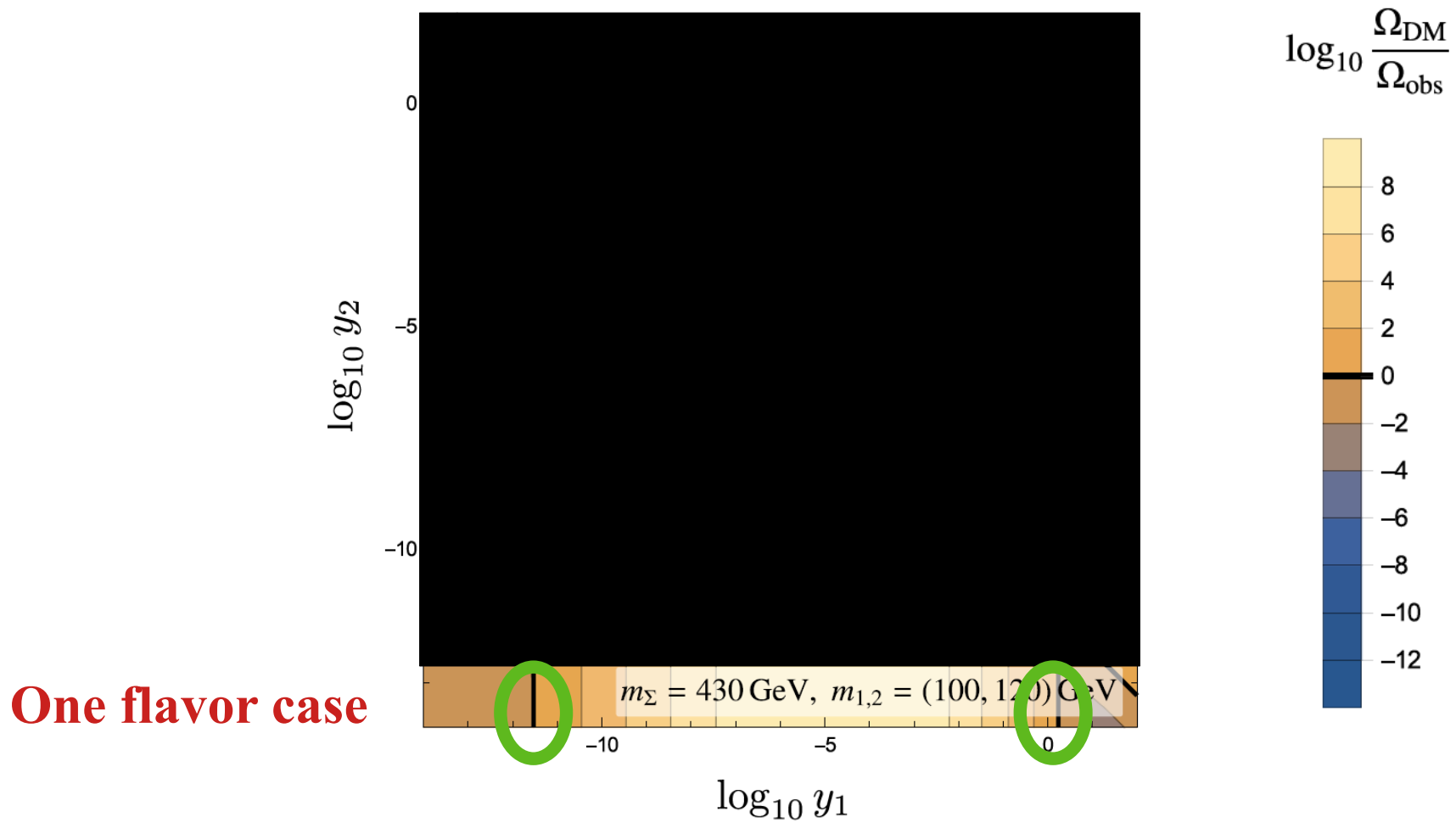


A toy model of multiflavor DM

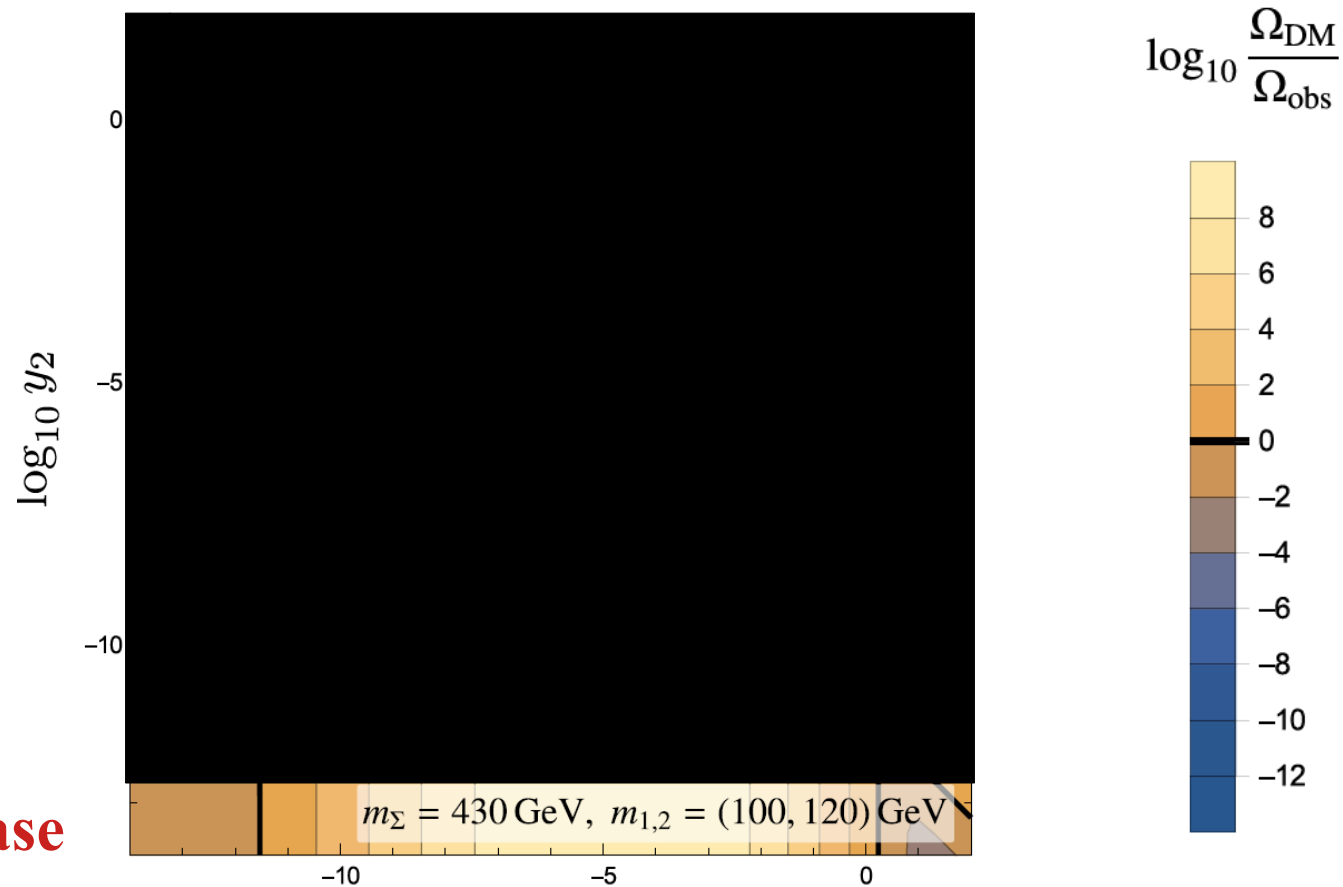
One flavor case



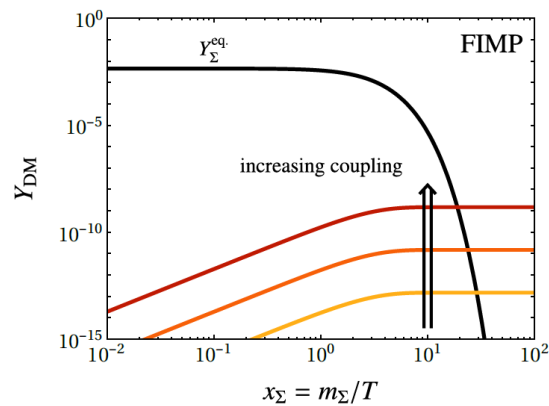
A toy model of multiflavor DM



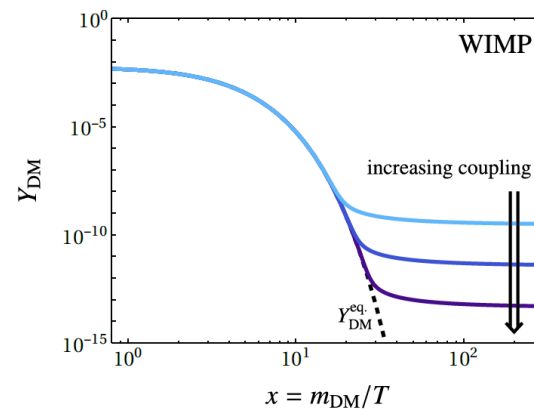
A toy model of multiflavor DM



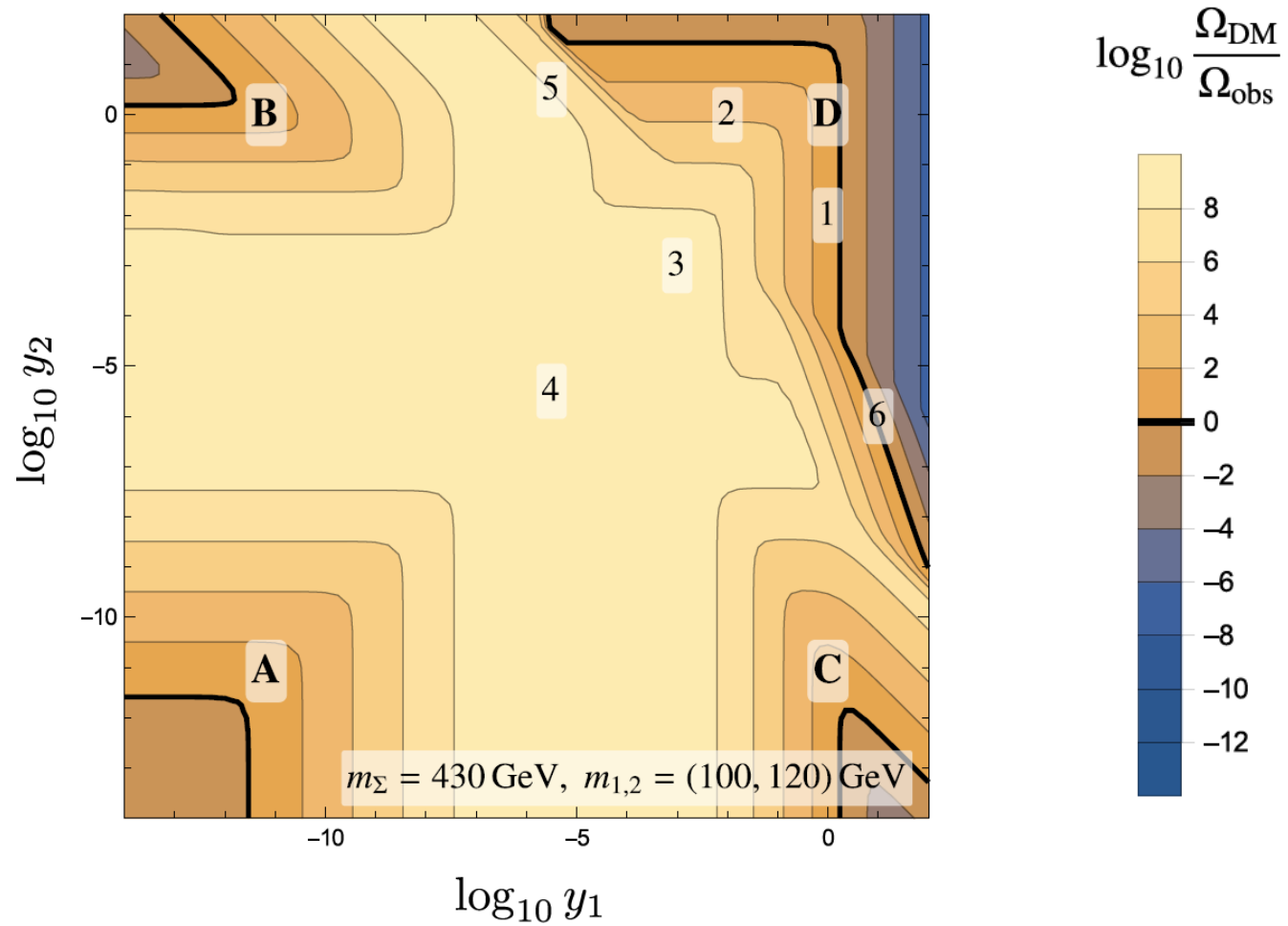
One flavor case



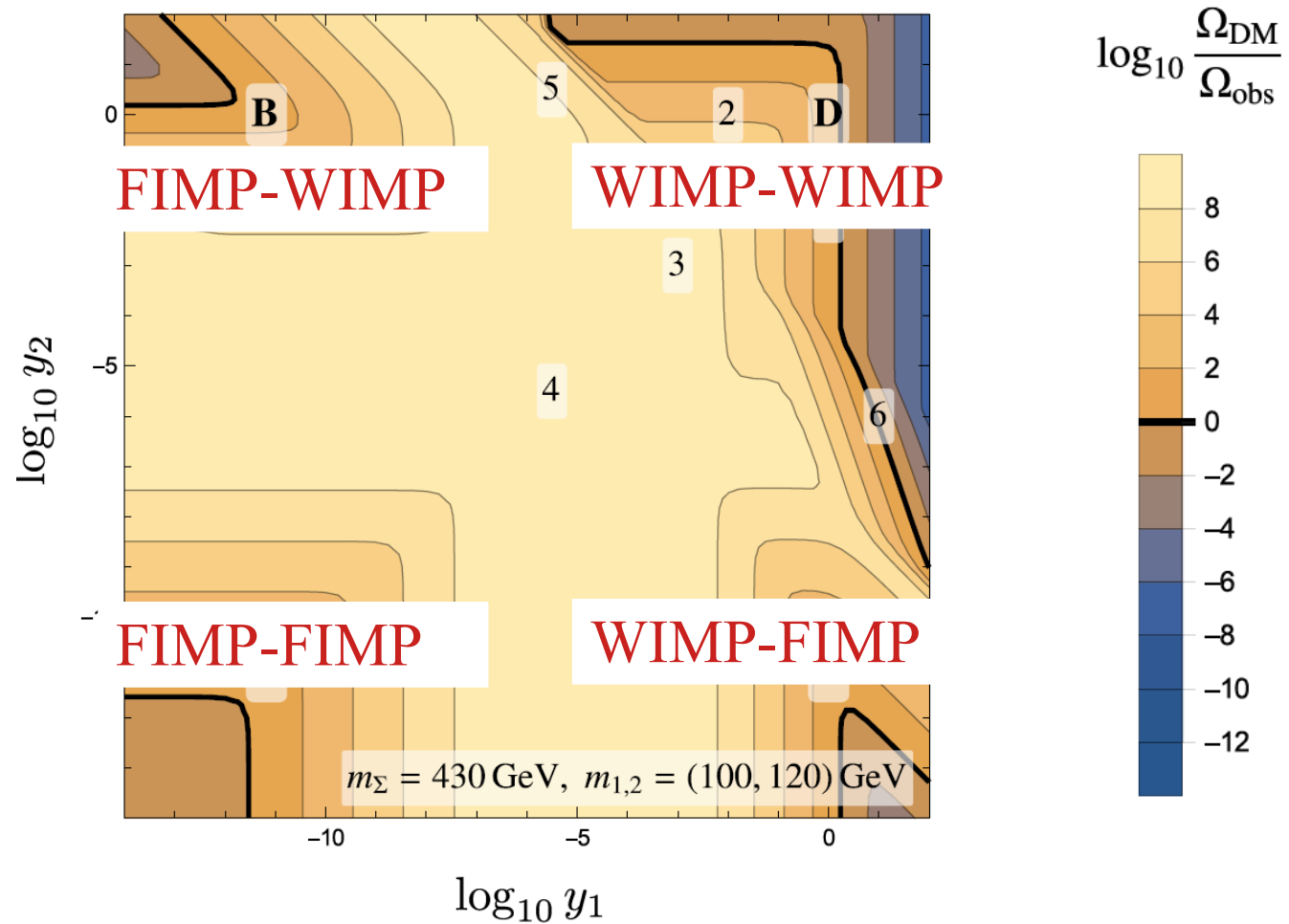
$\log_{10} y_1$



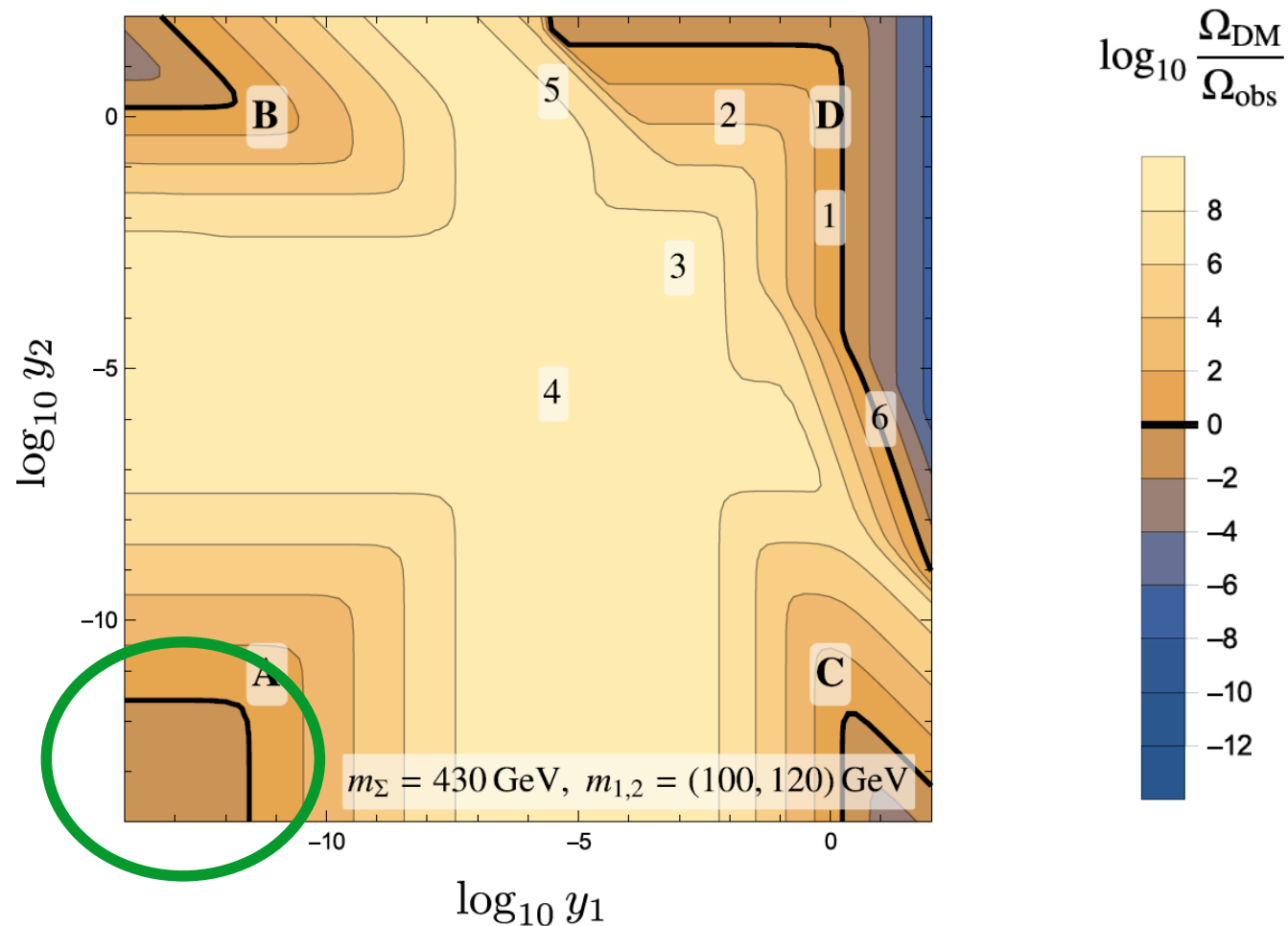
A toy model of multiflavor DM



A toy model of multiflavor DM

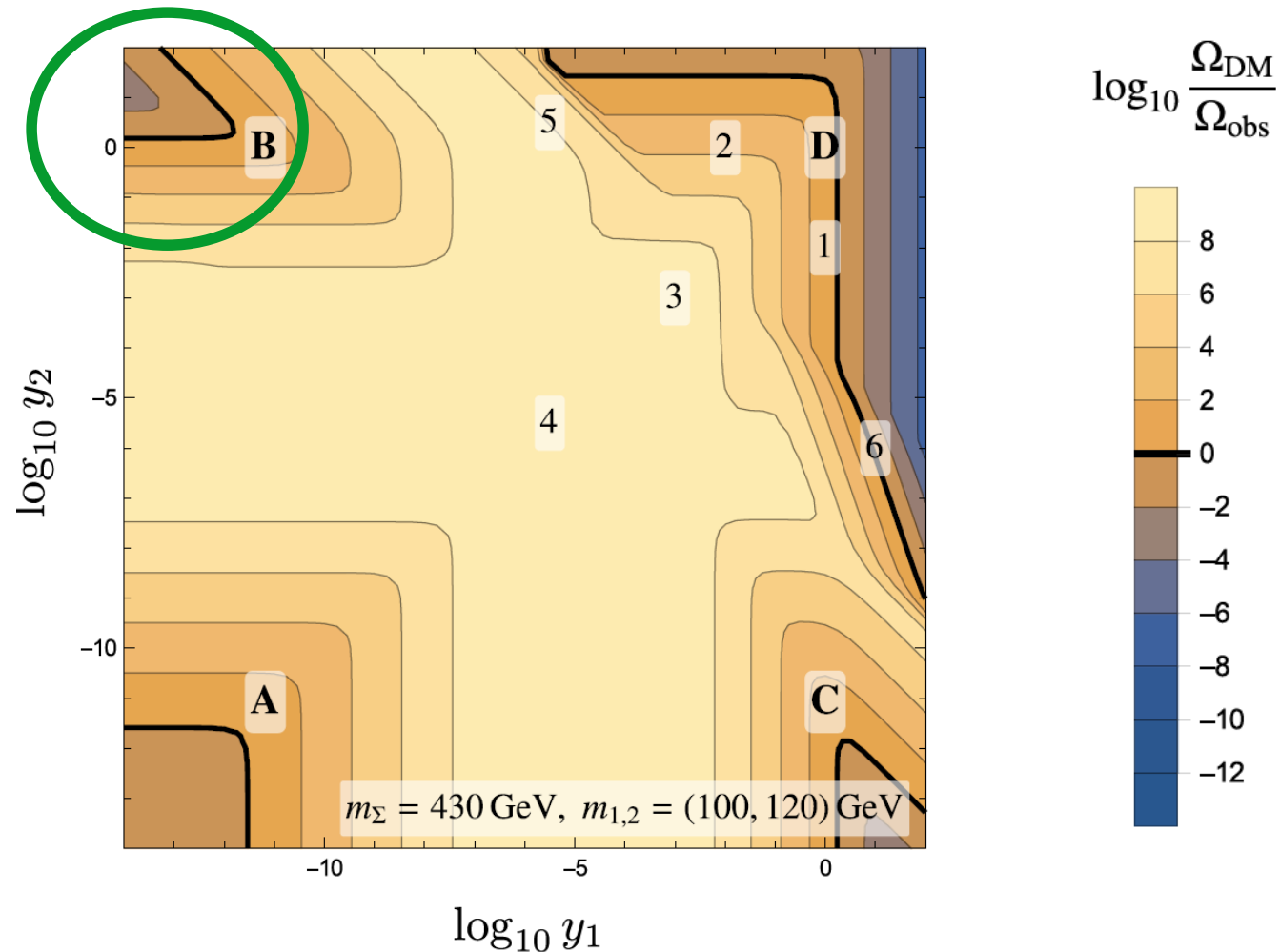


A toy model of multiflavor DM



ψ_1 and ψ_2 *not* thermalized. Abundances evolve independently.
Abundance set by $\Sigma \rightarrow \psi_i l$, $\Sigma l \rightarrow \psi_i \gamma$, etc.

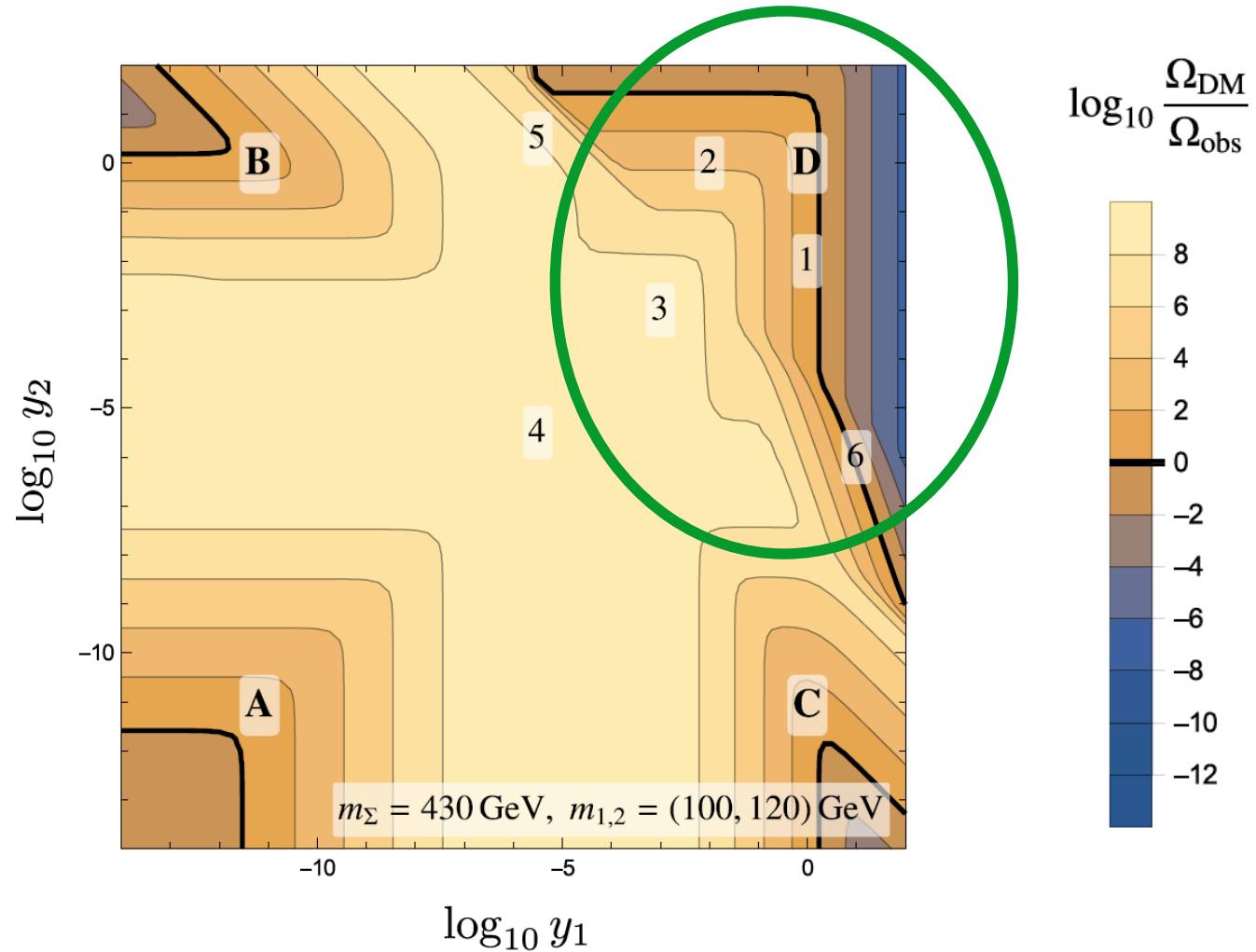
A toy model of multiflavor DM



ψ_2 thermalized. Abundance set by $\psi_2\psi_2 \rightarrow l^+l^-$

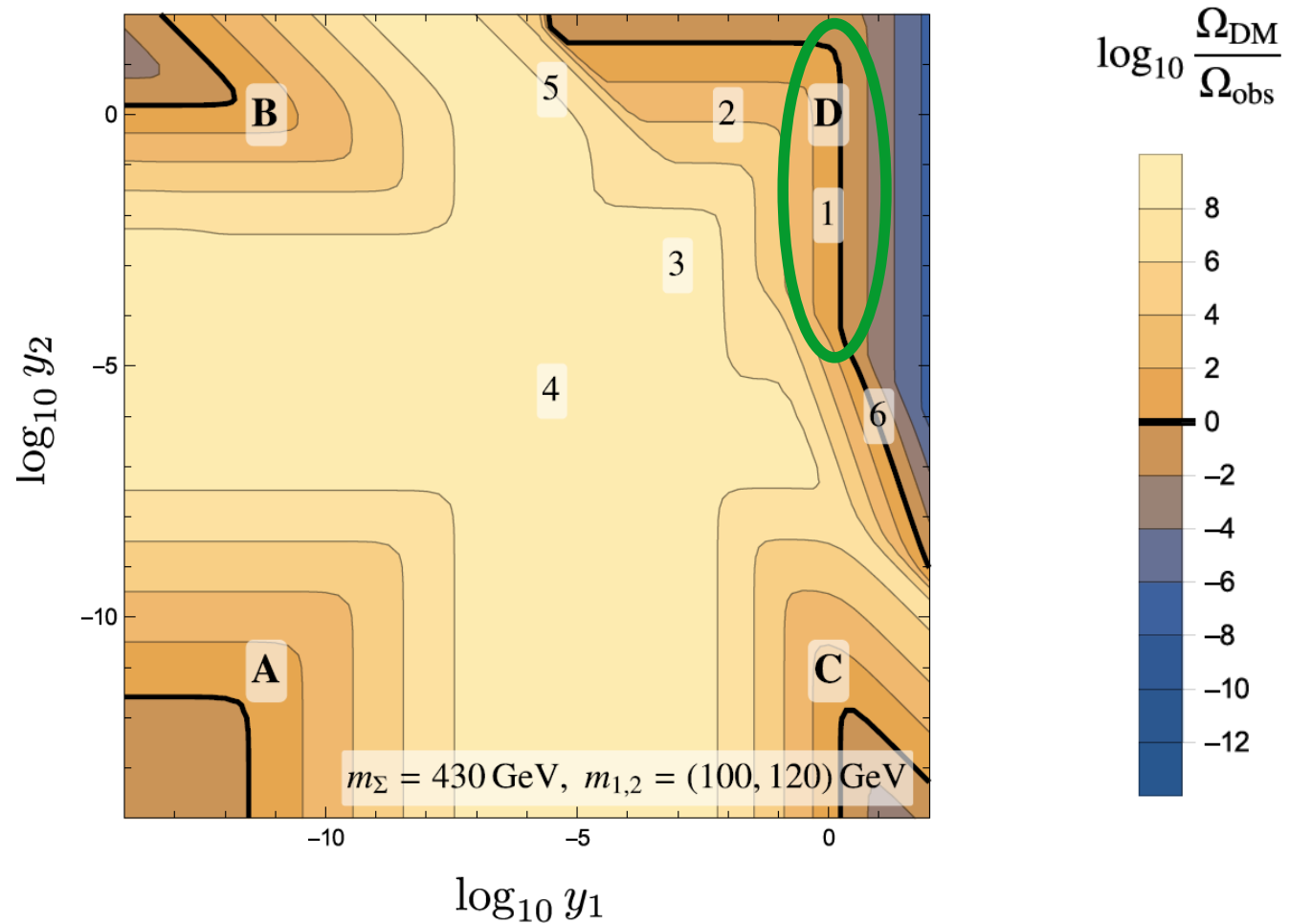
ψ_1 *not* thermalized. Abundance set by $\Sigma \rightarrow \psi_i l$, $\Sigma l \rightarrow \psi_i \gamma$, $\psi_2 l \rightarrow \psi_1 l$

A toy model of multiflavor DM



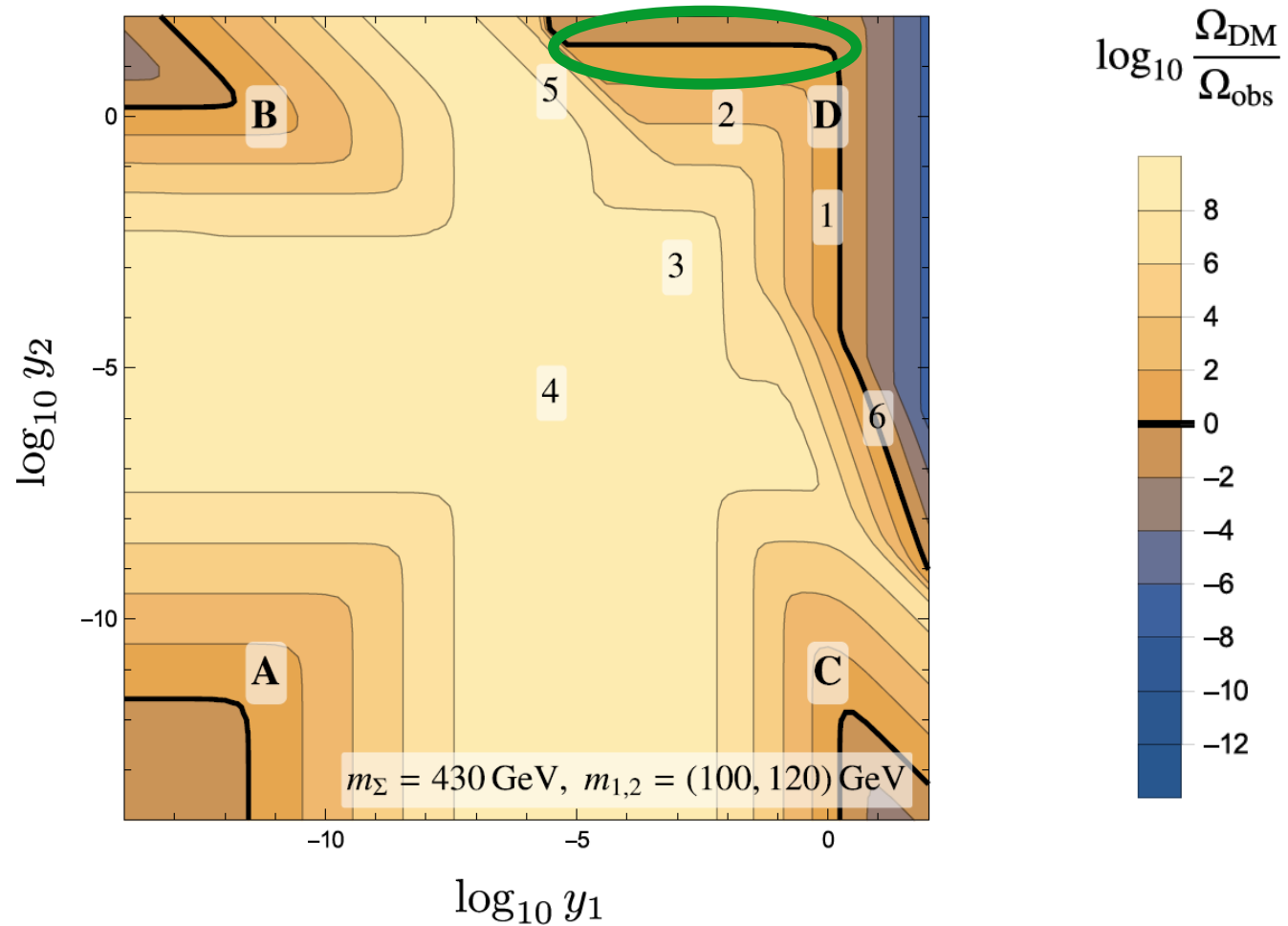
ψ_1 and ψ_2 thermalized.

A toy model of multiflavor DM



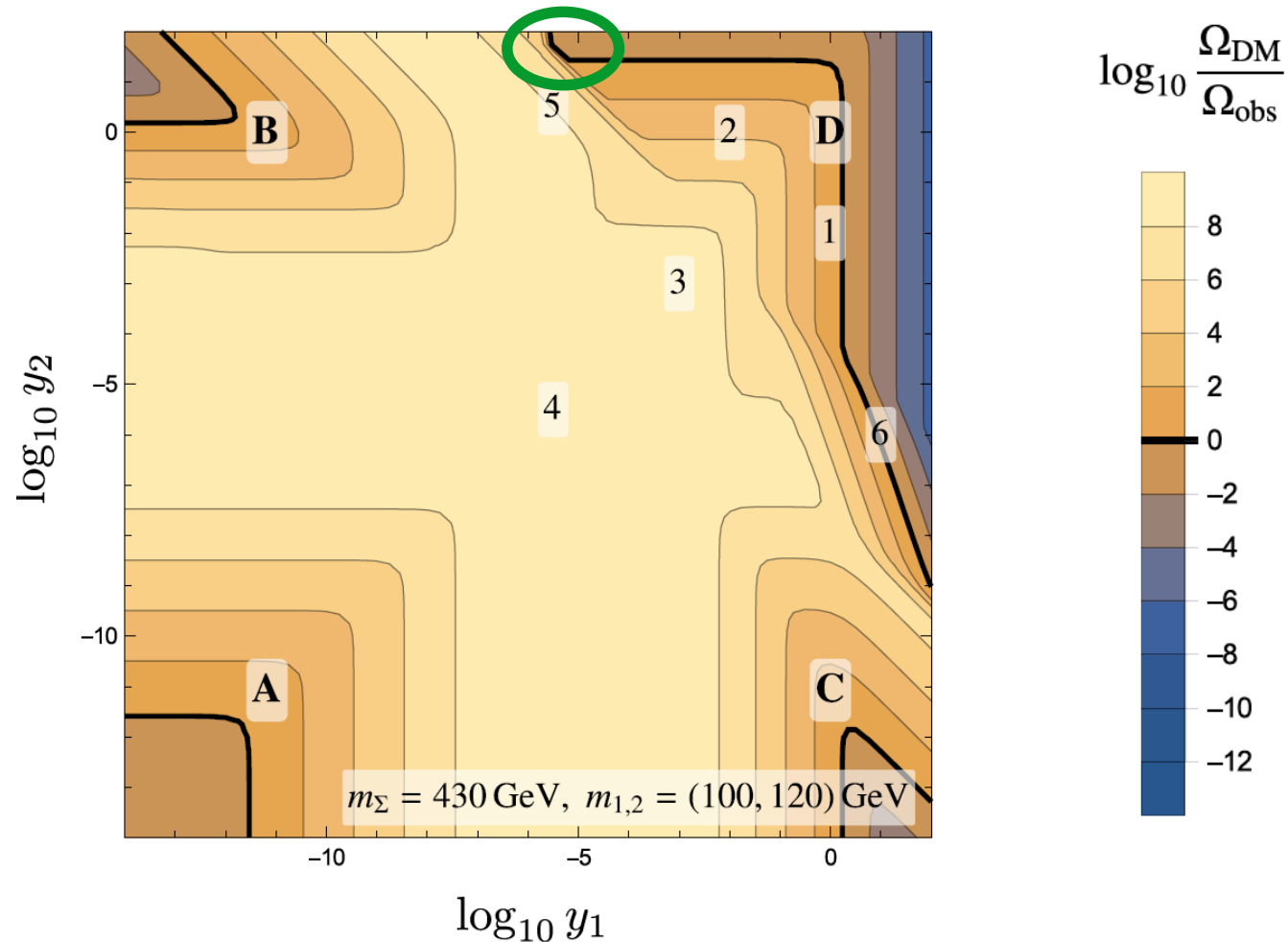
ψ_1 abundance set by $\psi_1\psi_1 \rightarrow l^+l^-$
 ψ_2 irrelevant

A toy model of multiflavor DM



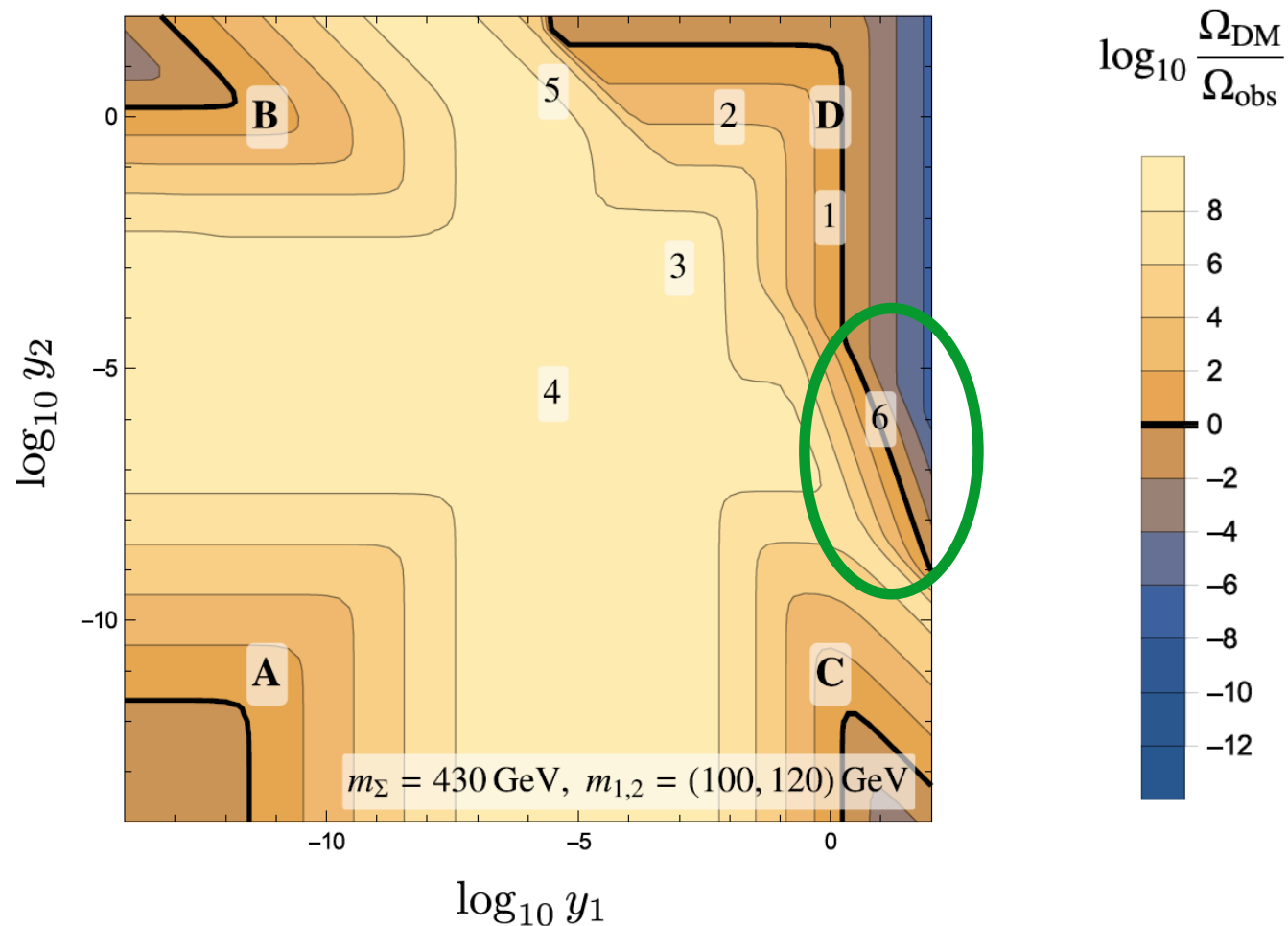
DM abundance set by ψ_2 coannihilation $\psi_2\psi_2 \rightarrow l^+l^-$

A toy model of multiflavor DM



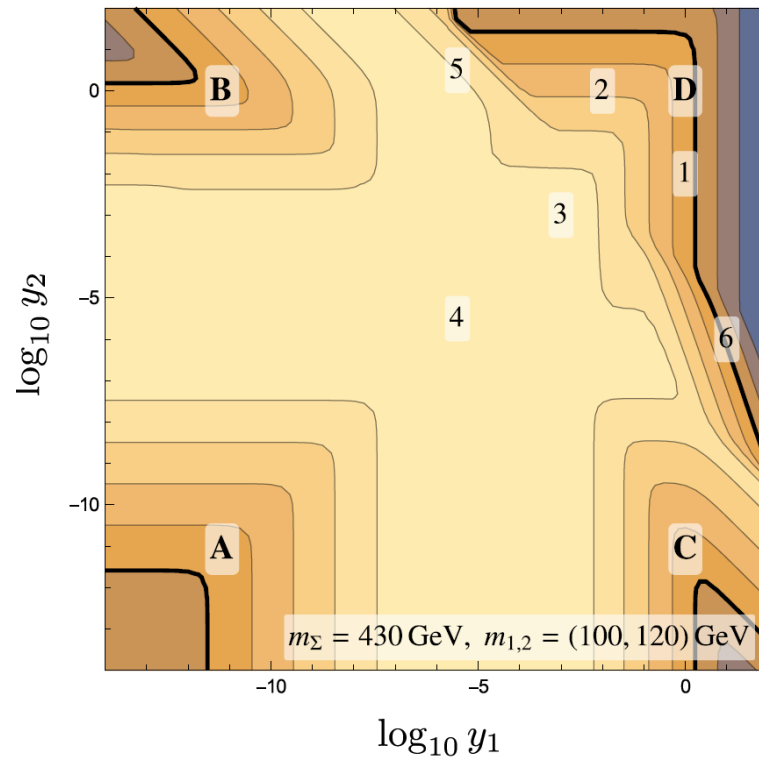
$\psi_1 \rightarrow \psi_2$ conversion driven freeze-out
 ψ_1 drops out of chemical equilibrium before ψ_2 coannihilation
becomes effective

A toy model of multiflavor DM



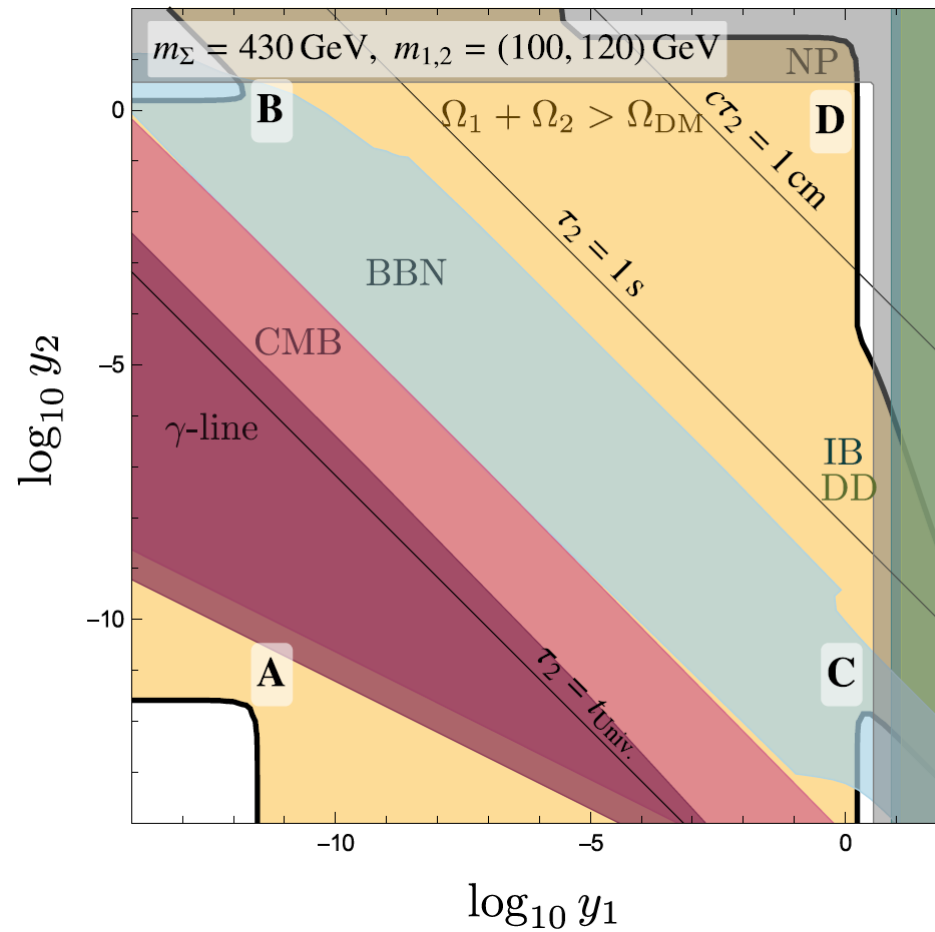
ψ_2 long-lived. DM abundance set by $\psi_1\psi_1 \rightarrow l^+l^-$, $\psi_2 l \rightarrow \psi_1 l$,
 $\psi_2 \rightarrow \psi_1 l^+l^-$

A toy model of multiflavor DM

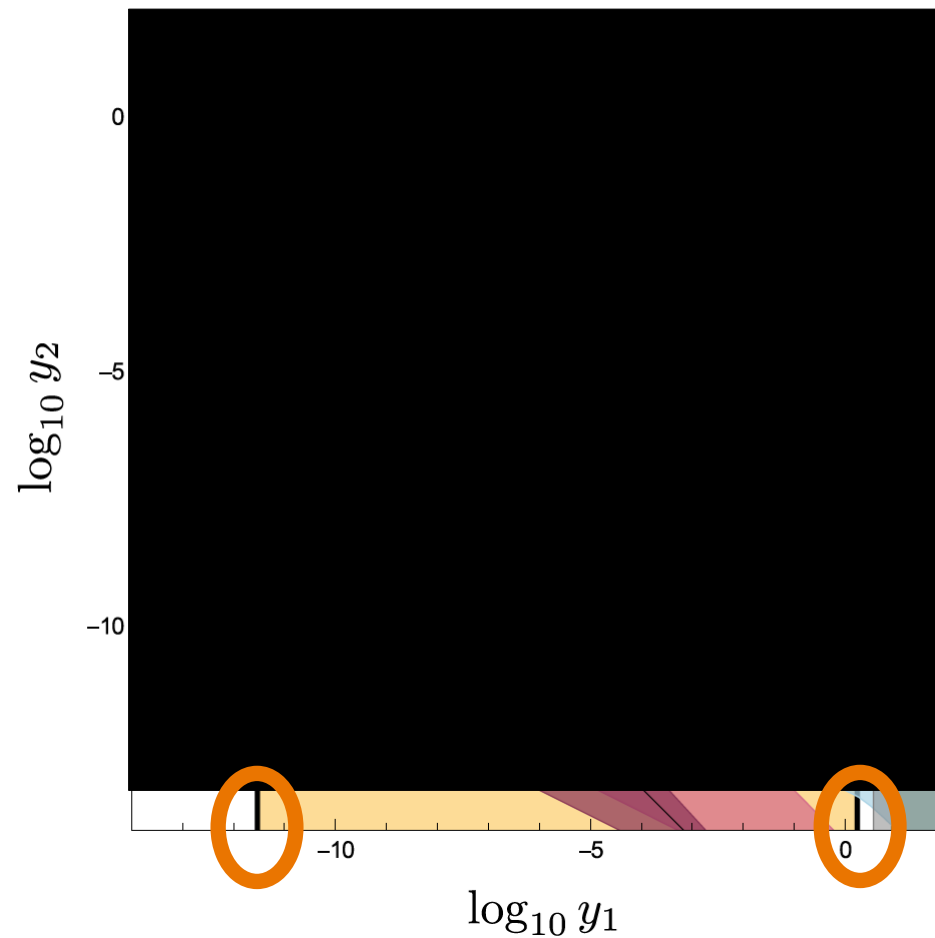


- With one DM flavor, the value of the Yukawa coupling is fixed.
- With two DM flavors, many more possibilities. Larger couplings are compatible with the observed DM abundance \rightarrow enhanced signals
- Bonus: new signals from $\psi_2 \rightarrow \psi_1 \gamma$, $\psi_2 \rightarrow \psi_1 e^+ e^-$, etc.

Signatures of multi-flavor DM scenarios



Signatures of multi-flavor DM scenarios



One flavor case.

FIMP

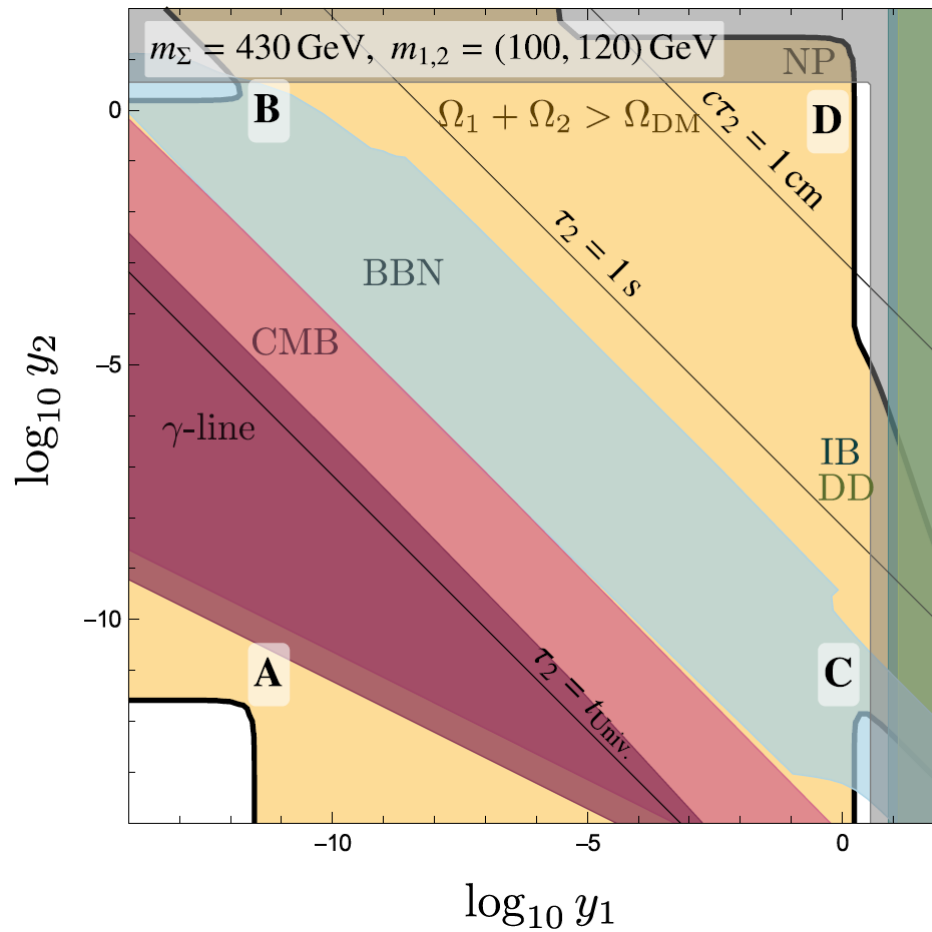
$$\Sigma \rightarrow l\psi_1$$

WIMP

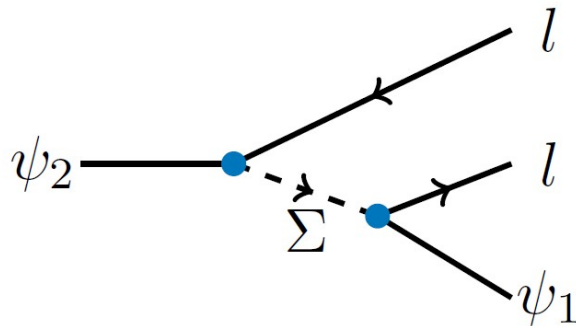
$$\psi_1\psi_1 \rightarrow l^+l^-\gamma$$

$$\psi_1 N \rightarrow \psi_1 N \text{ (via anapole moment)}$$

Signatures of multi-flavor DM scenarios

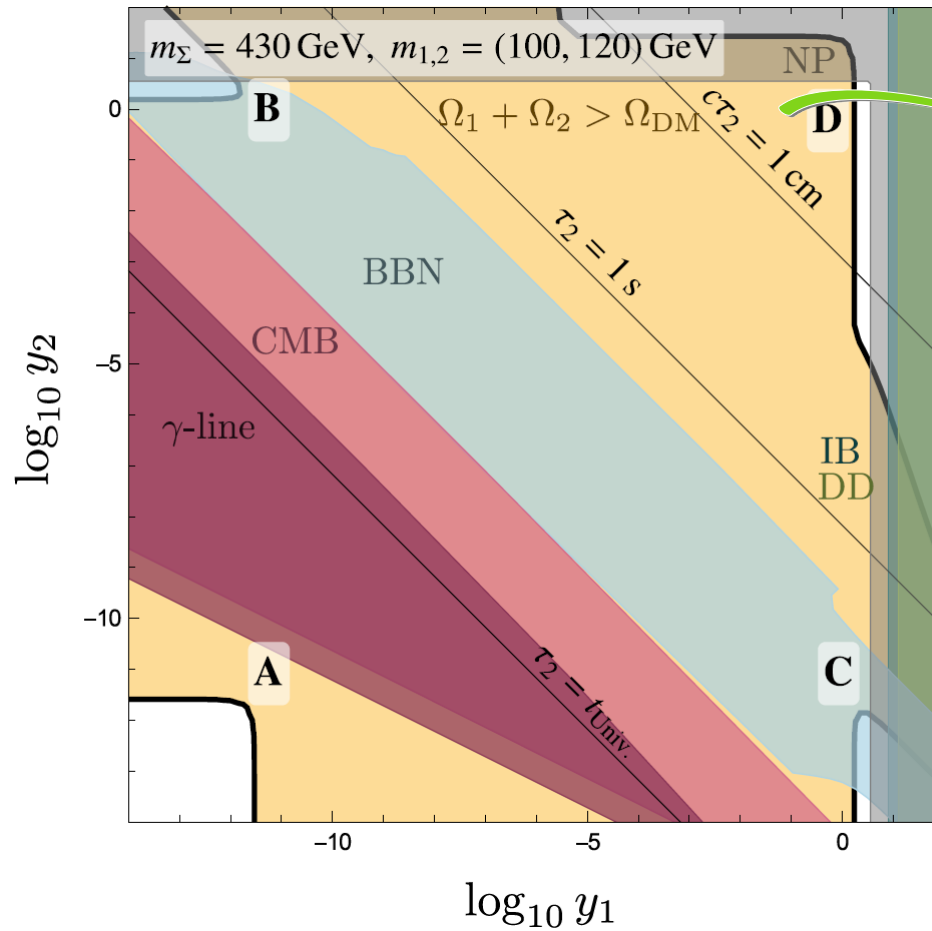


Isocontours of ψ_2 lifetime

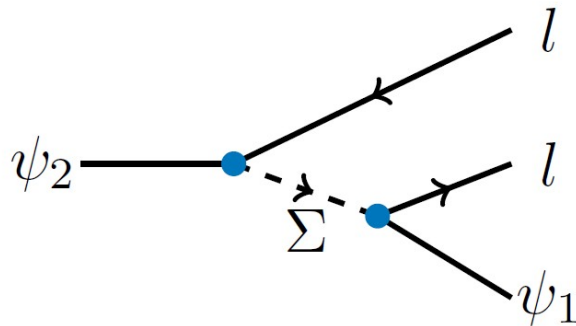


$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

Signatures of multi-flavor DM scenarios

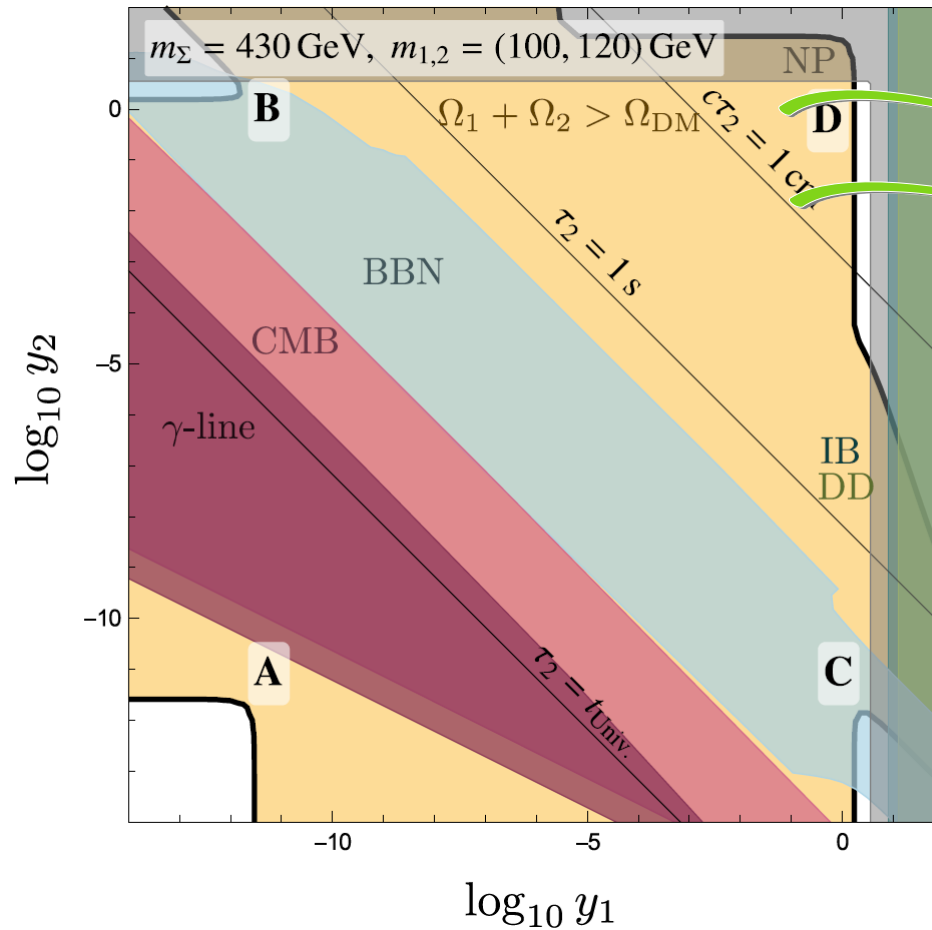


Prompt decays in a detector
hard leptons + \cancel{E}_T



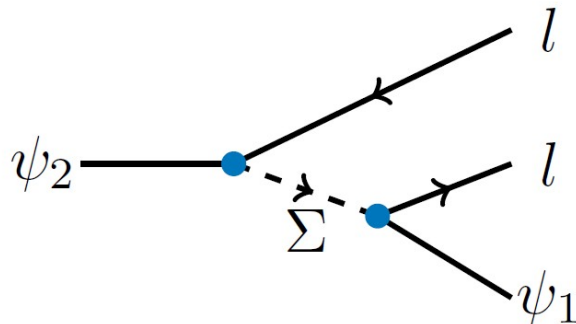
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Signatures of multi-flavor DM scenarios



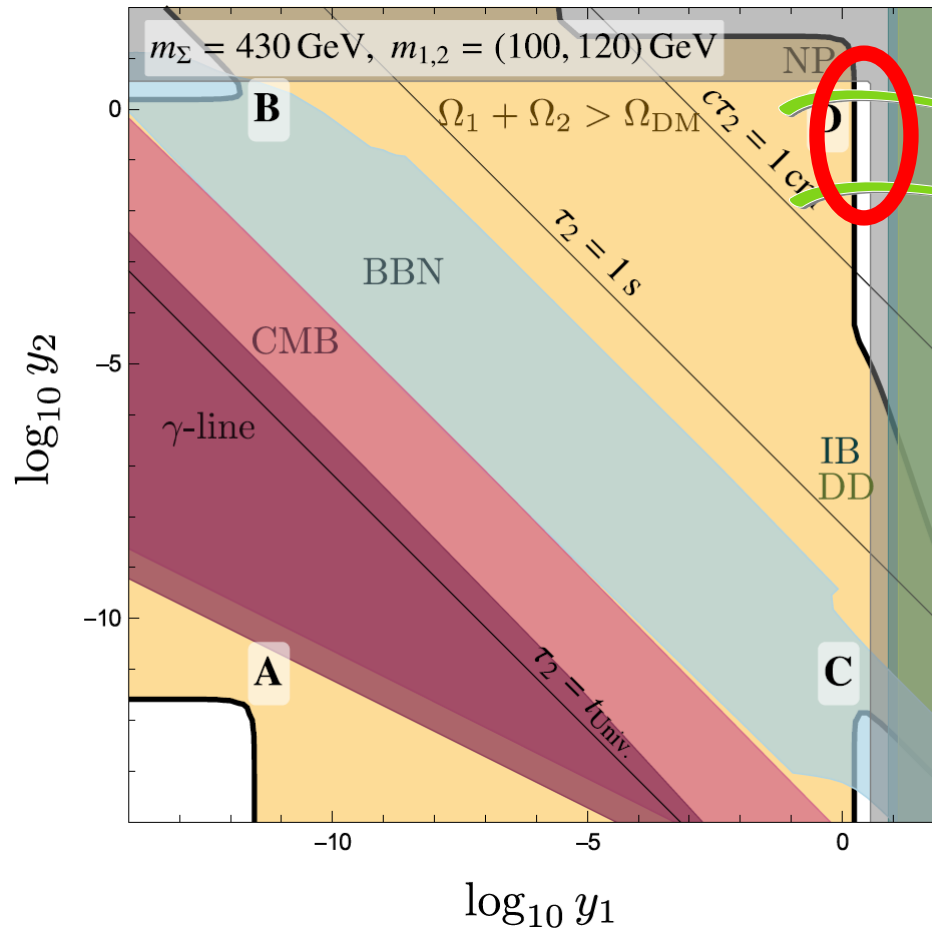
Prompt decays in a detector
hard leptons + \cancel{E}_T

Displaced signatures



$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

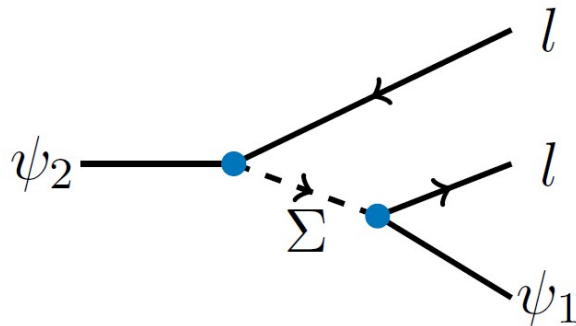
Signatures of multi-flavor DM scenarios



Prompt decays in a detector
hard leptons + \cancel{E}_T

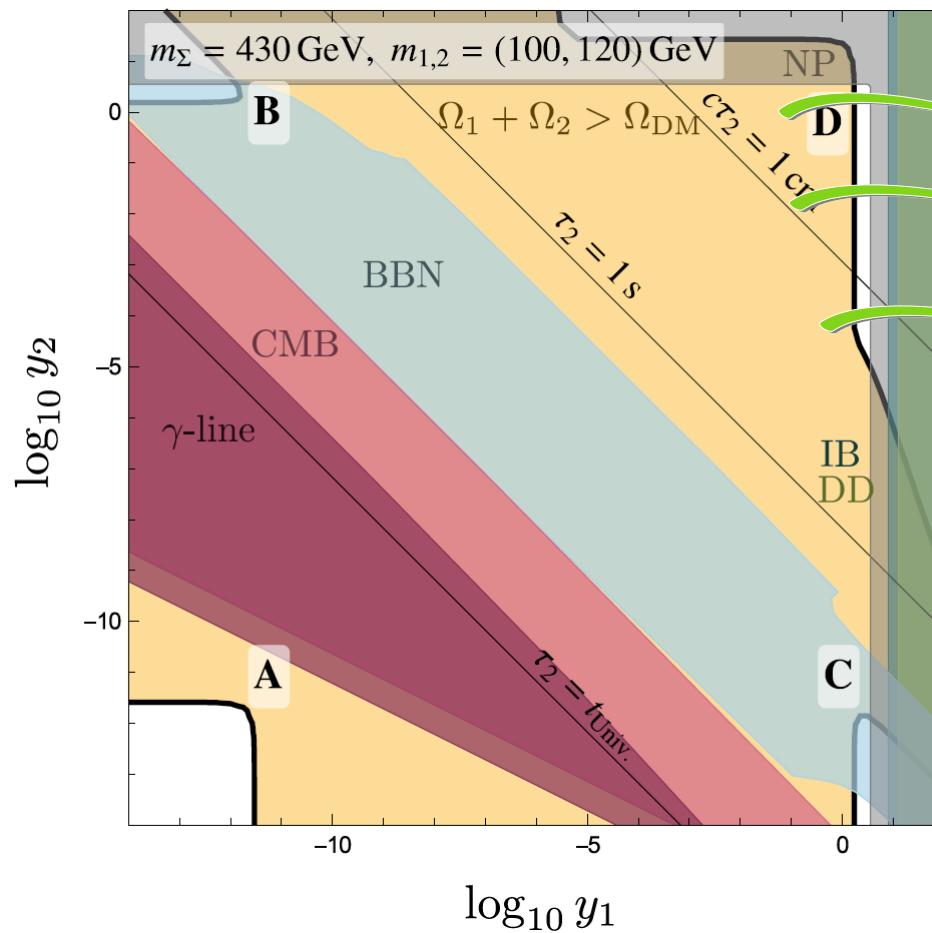
Displaced signatures

Possible signals at colliders



$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

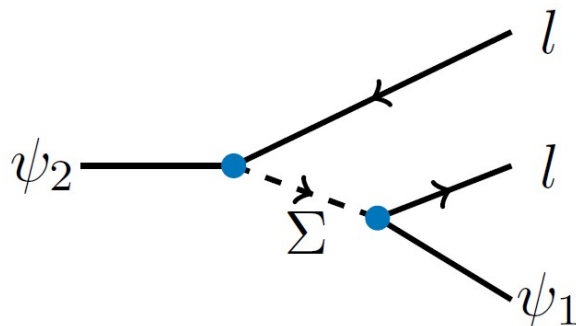
Signatures of multi-flavor DM scenarios



Prompt decays in a detector
hard leptons + \cancel{E}_T

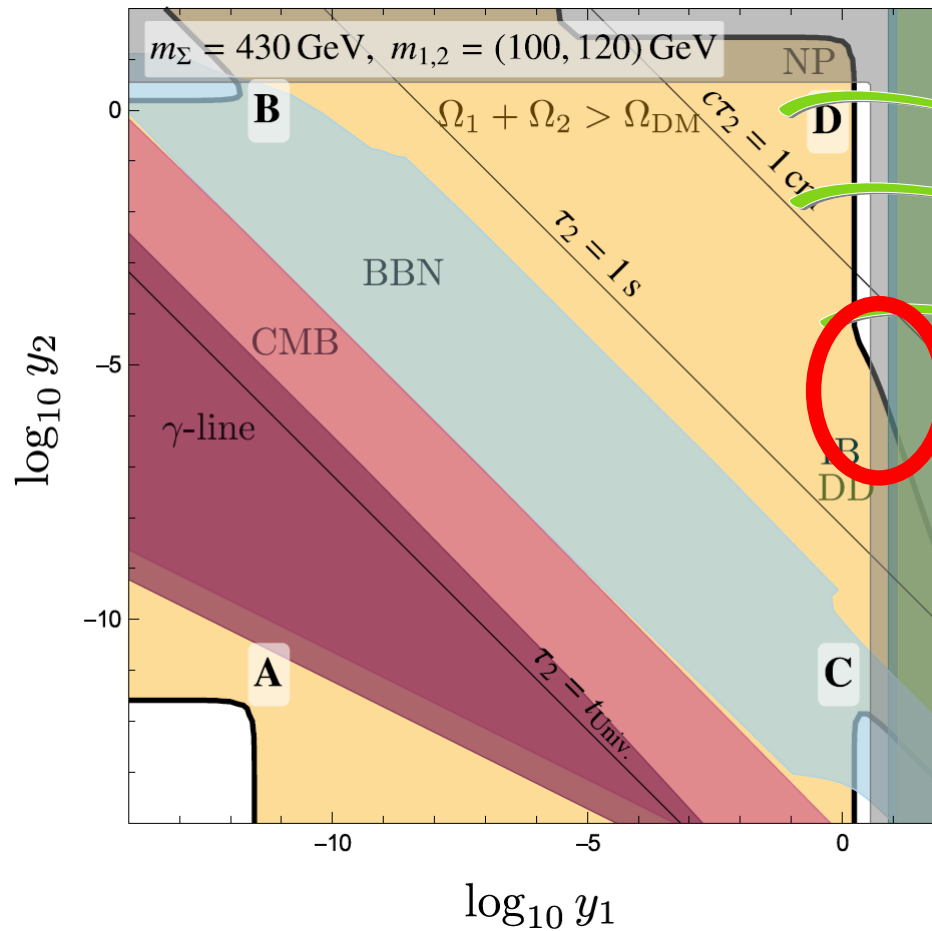
Displaced signatures

ψ_2 decays after ψ_1
freeze-out.



$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

Signatures of multi-flavor DM scenarios



Prompt decays in a detector
hard leptons + \cancel{E}_T

Displaced signatures

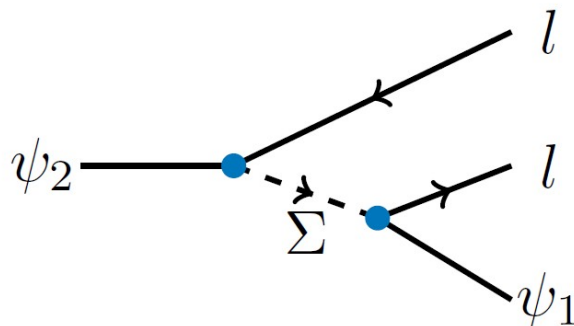
ψ_2 decays after ψ_1
freeze-out.

Possible signals in direct
and indirect searches

$$\psi_1 \psi_1 \rightarrow l^+ l^- \gamma$$

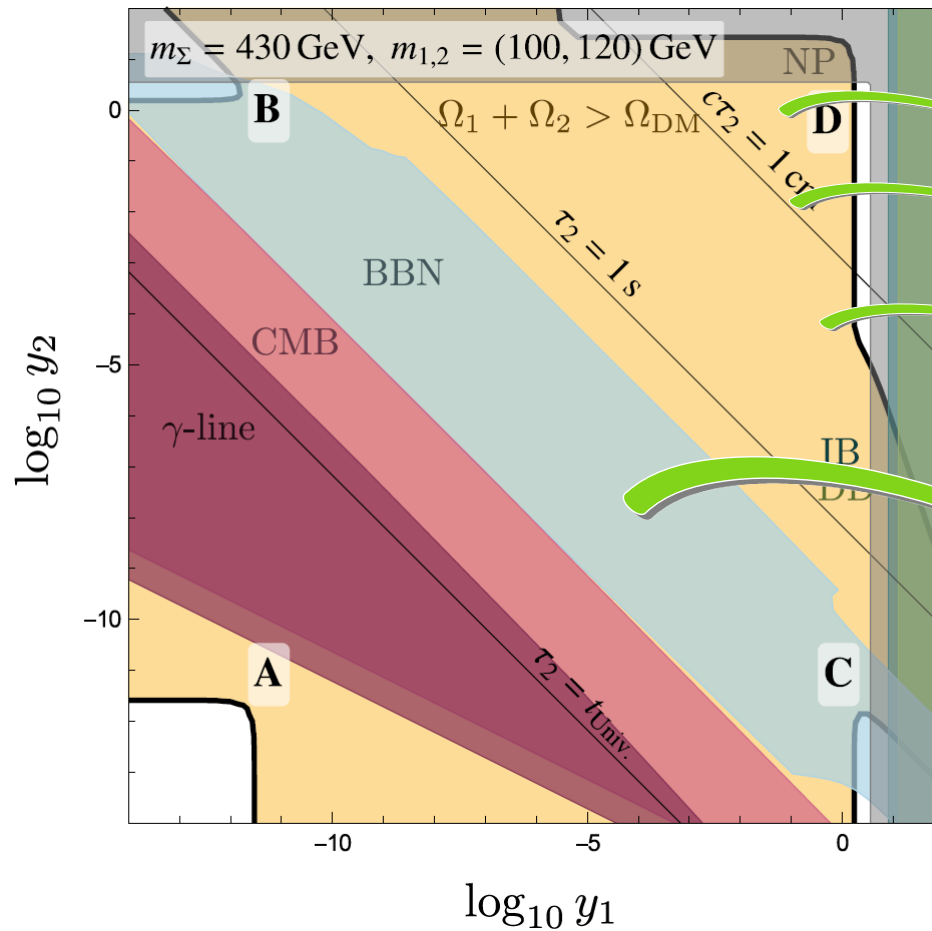
$$\psi_1 N \rightarrow \psi_1 N$$

$$\text{Rate} \propto y_1^4$$



$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

Signatures of multi-flavor DM scenarios

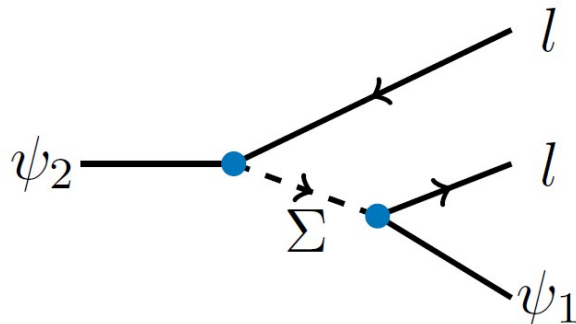


Prompt decays in a detector
hard leptons + \cancel{E}_T

Displaced signatures

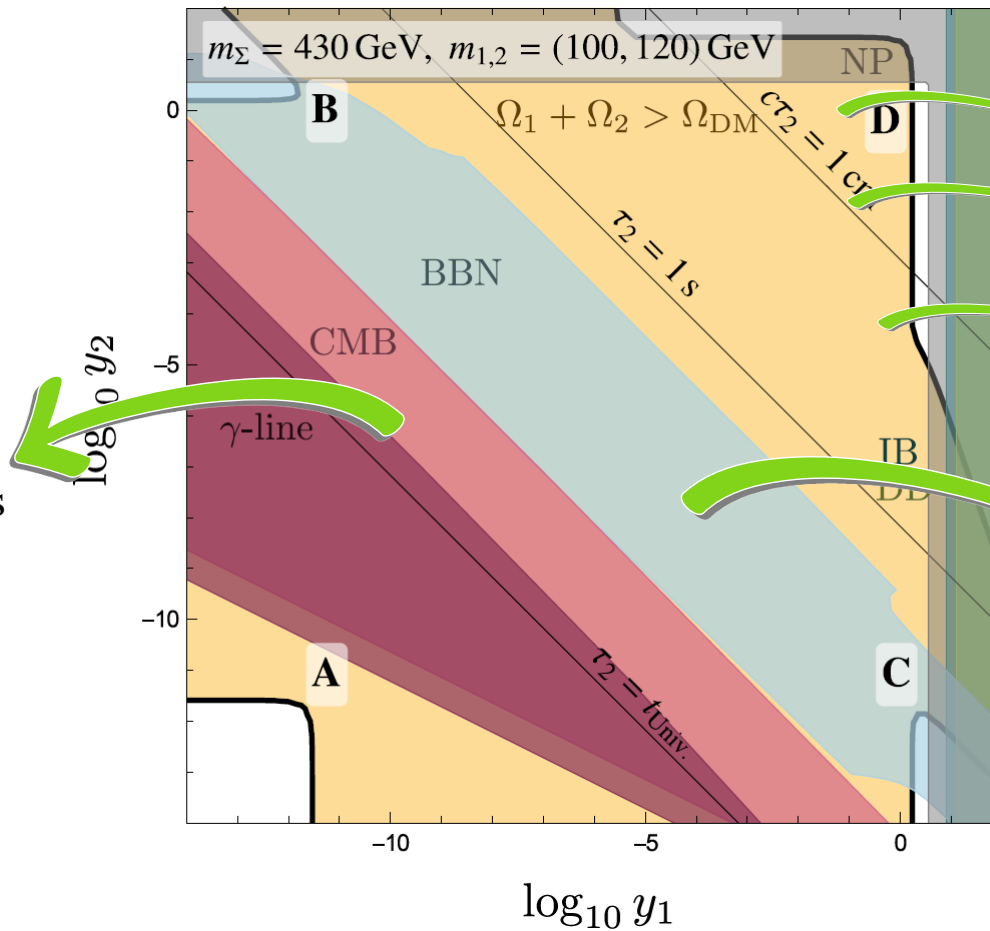
ψ_2 decays after ψ_1
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Abundances of primordial
nuclei due to exotic energy
injection.



$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

Signatures of multi-flavor DM scenarios



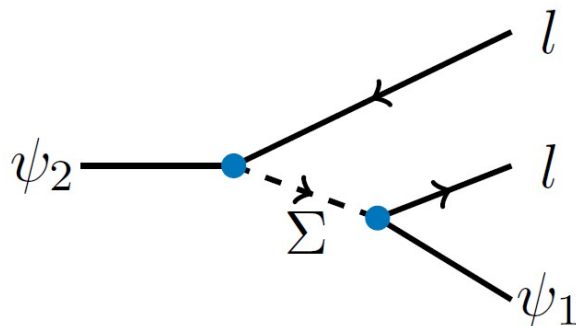
Spectral distortions in the CMB

Prompt decays in a detector
hard leptons + \cancel{E}_T

Displaced signatures

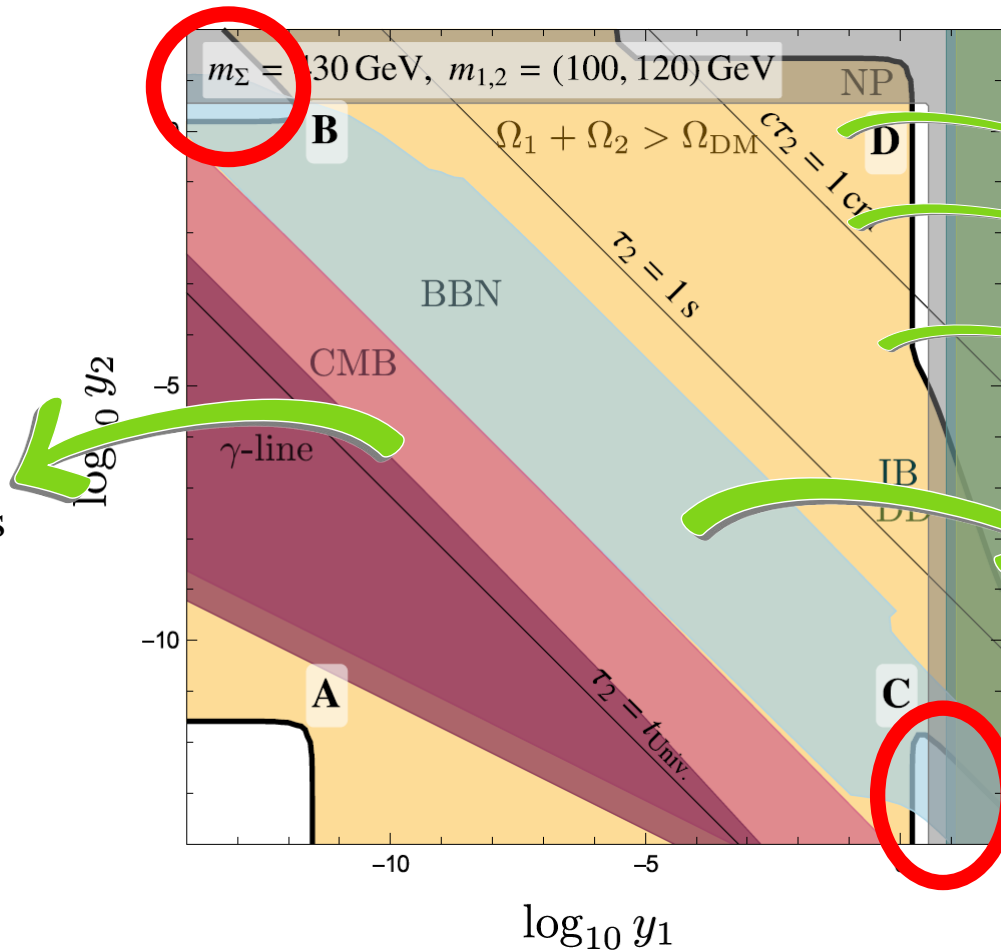
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Signatures of multi-flavor DM scenarios



Spectral distortions in the CMB

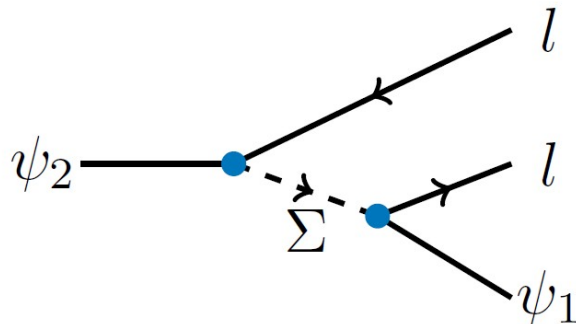
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Displaced signatures

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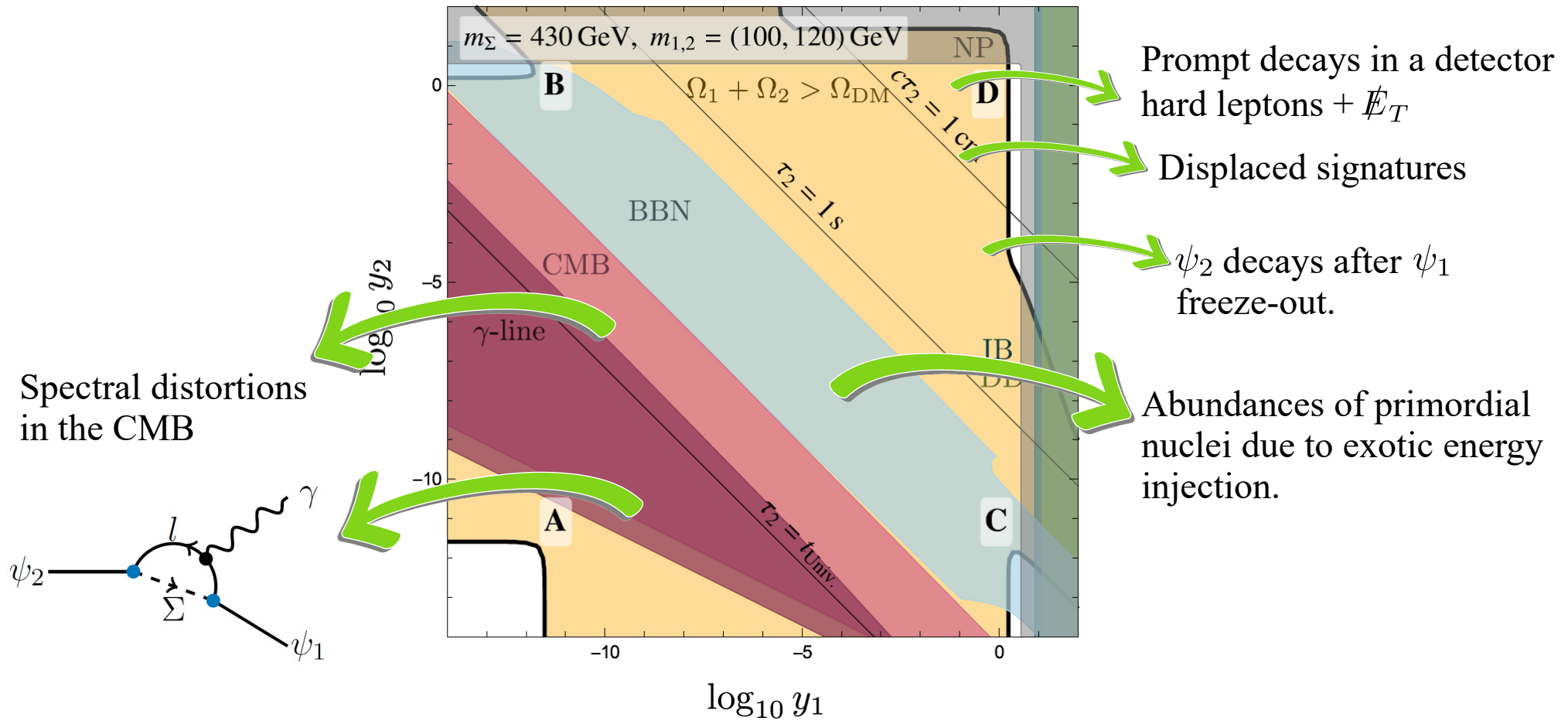
Abundances of primordial
nuclei due to exotic energy
injection.

Possible signals in
cosmological observations

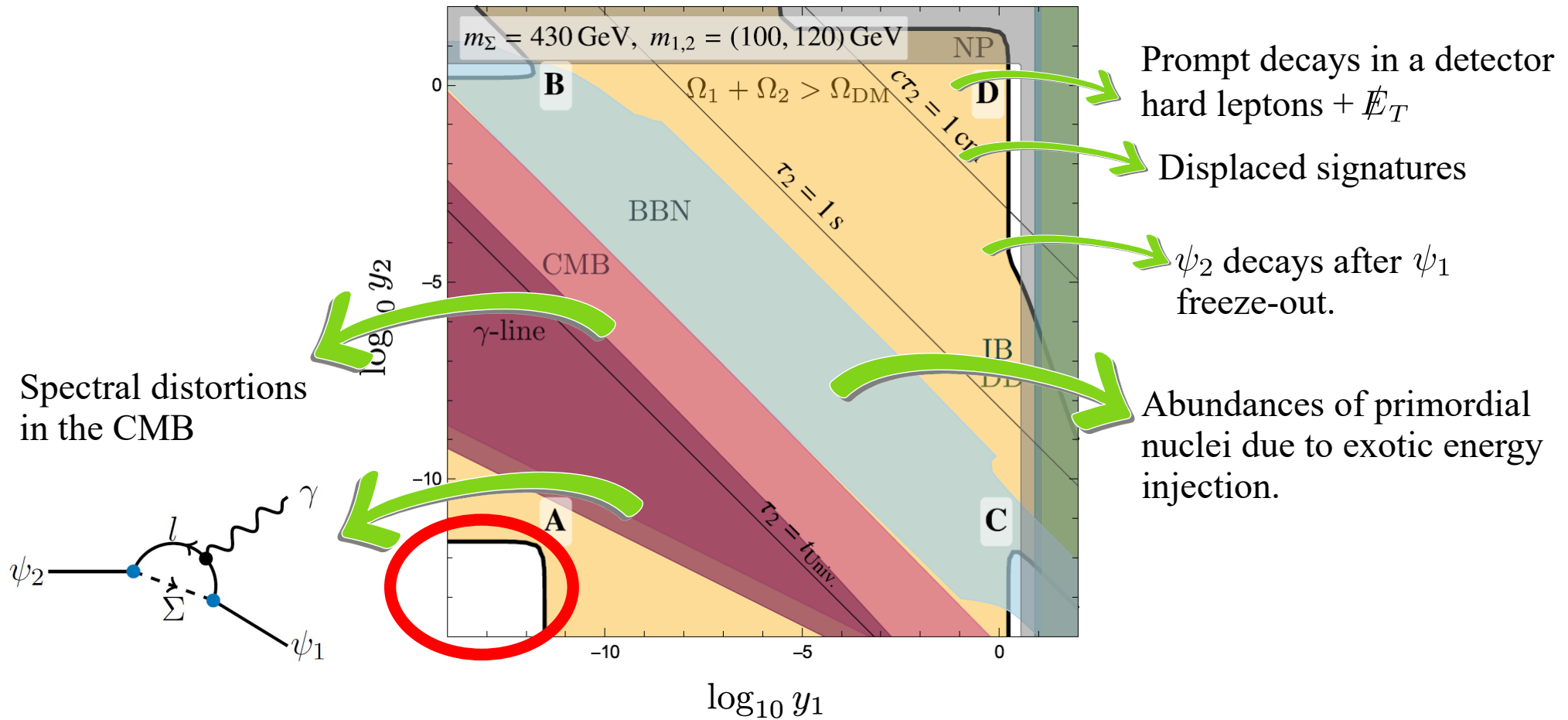


$$\Gamma \sim \frac{y_1^2 y_2^2}{128\pi^3} \frac{m_{\psi_2}^5}{m_\Sigma^4}$$

Signatures of multi-flavor DM scenarios



Signatures of multi-flavor DM scenarios



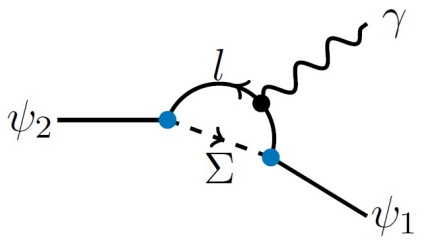
Prompt decays in a detector
hard leptons + \cancel{E}_T

Displaced signatures

ψ_2 decays after ψ_1
freeze-out.

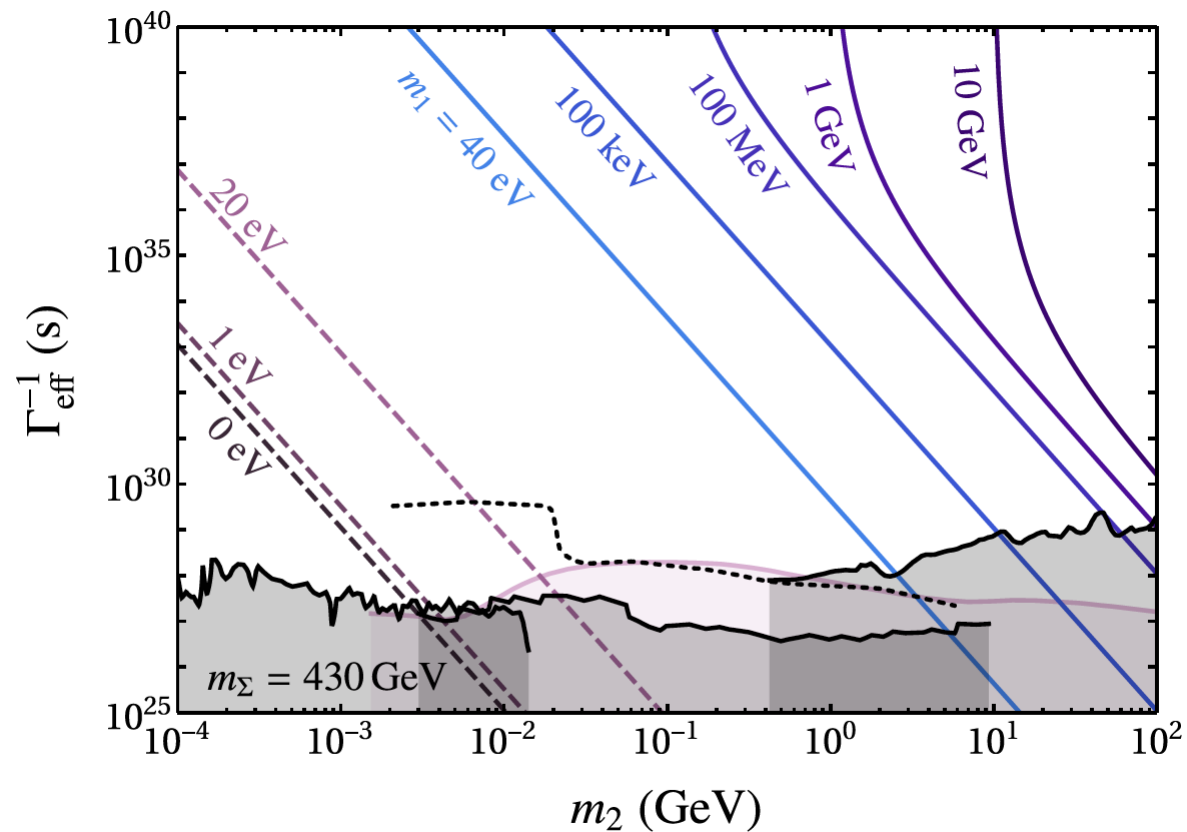
Abundances of primordial
nuclei due to exotic energy
injection.

Spectral distortions
in the CMB



Possible signals in γ -ray
or cosmic ray experiments

Signatures of multi-flavor DM scenarios



Conclusions

- It is not unlikely that the dark matter particle could come in several flavors/generations.
- Even if the heavier generations are not present today in our Universe, they could have played a role in the dark matter production (may be also in generating DM asymmetries??)
- The existence of several flavors could enhance the detection rate at experiments, or lead to new signatures.

